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Review and prospect of supersonic business jet design

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Abstract

This paper reviews the environmental issues and challenges appropriate to the design of supersonic business jets (SSBJs). There has been a renewed, worldwide interest in developing an environmentally friendly, economically viable and technologically feasible supersonic transport aircraft. A historical overview indicates that the SSBJ will be the pioneer for the next generation of supersonic airliners. As a high-end product itself, the SSBJ will likely take a market share in the future. The mission profile appropriate to this vehicle is explored considering the rigorous environmental constraints. Mitigation of the sonic boom and improvements aerodynamic efficiency in flight are the most challenging features of civil supersonic transport. Technical issues and challenges associated with this type of aircraft are identified, and methodologies for the SSBJ design are discussed. Due to the tightly coupled issues, a multidisciplinary design, analysis and optimization environment is regarded as the essential approach to

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Abbreviations: A_e, equivalent area; CAPAS, CAD-based Automatic Panel Analysis System; CFD, Computational Fluid Dynamics; CFR, Code of Federal Regulations; C.G., Centre of Gravity; CIAM, Central Institute of Aviation Motors; CS, Certification Specifications; CST, Class Shape Transformation; DARPA, Defense Advanced Research Projects Agency; E.I., emission indices; GAC, Gulfstream Aerospace Corporation; GIT, Georgia Institute of Technology; HISAC, High Speed Aircraft; HSCT, High Speed Civil Transport; HSR, High Speed Research; ICAO, International Civil Aviation Organization; JAXA, Japan Aerospace Exploration Agency; L/D, lift to drag ratio; LFC, laminar flow control; Ma, Mach number; MDAO, Multidisciplinary Design Analysis and Optimization; MDO, Multidisciplinary Design Optimization; mSv, millisievert; NASA, National Aeronautics and Space Administration; NLF, natural laminar flow; PAX, passenger; PLdB, perceived loudness level; psf, pounds per square foot; QSP, Quiet Supersonic Platform; QSST, Quiet Supersonic Transport; S3TD, Silent Supersonic Technology Demonstrator; SFC, specific fuel consumption; SSBJ, Supersonic Business Jet; SST, Supersonic Transport; TRL, technology readiness level; TSS, Technical Supersonic Standard; UIUC, University of Illinois at Urbana-Champaign; VCE, variable cycle engine; VSP, Vehicle Sketch Pad

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the creation of a low-boom low-drag supersonic aircraft. Industrial and academic organizations have an interest in this type of vehicle are presented. Their investments in SSBJ design will hopefully get civil supersonic transport back soon.

Keywords: Supersonic transport, Supersonic business jet, Sonic boom, Aircraft design

Contents

1. Introduction

Since the retirement of Concorde's airline service in 2003, there is no more civil supersonic transport. The environmental concerns (sonic boom, noise, emissions, etc.) raised by Concorde have been the major barriers for future civil supersonic aircraft. The fundamental problem preventing the return of supersonic flight is the sonic boom at ground level. However, the public's perceived acceptance of the sonic boom intensity is still uncertain. Since the weight and size of a supersonic aircraft have first-order effects on the intensity of the sonic boom signature, it has been deemed nearly impossible to create a low-boom level with a heavier and larger conventional aircraft.

Though, for a wide range of customers the low price airline is attractive, there still exist customers (such as executives or heads of state) who attribute great value to time. Recognition of the value of time has led to increased interest in the feasibility of small supersonic business jets (SSBJ). Double the cruise speed could result in half the time in the air. Operational flexibility, safety and privacy working environment, and adequate ambience for fostering social contacts add value to SSBJs [1]. The unit price and direct operation costs should be viable for both manufacturers and customers.

The interest of supersonic civil flight is not only driven by enterprising human spirit or profit seeking but also by technology itself. The basic technical capability for the supersonic cruise has existed for decades and the technology has improved considerably since Concorde. The variable cycle engine concept and acoustic problems caused by the inlet and nozzle require more development to solve. Sonic boom mitigation concepts still need further ground and flight testing.

Therefore, environmentally friendly, economically viable and technologically feasible characteristics are required for any future supersonic airliner.

There have been prominent publications on SSBJ design review. The National Research Council analysed the design challenges and critical solutions appropriate to supersonic transport [2]. P. A. Henne compiled Gulfstream research on the SSBJ [3]. Wu Li at NASA has been developing design tools for low-boom supersonic aircraft [4-9]. Stanford University publishes integrated study on SSBJ design [10-13]. Cranfield University has engaged in research into the preliminary and detail design of the SSBJ and is now developing a multidisciplinary design analysis and optimization methodology appropriate to SSBJ. H. Smith highlight the design issues of SSBJ [14]. Despite these efforts, no comprehensive review of emerging trends and concepts on SSBJ design has ever been undertaken. The aim of this paper is to review relevant publications in order to identify state-of-art concepts and challenges on SSBJ design.

To develop a successful supersonic transport, it is not enough to concentrate on the vehicle itself. This paper investigates the design of SSBJs from a systems point of view. Section 2 provides a brief historical background of supersonic airliner development and the derivation of SSBJs. The market potential of the SSBJ is analysed in Section 3. In Section 4, industry and academic organizations that are interested in the SSBJ design are investigated. Section 5 defines the mission requirements for SSBJs in terms of range, Mach number, cruise altitude, seating capacity, environmental issues, and airworthiness. The main technological challenges and solutions appropriate to SSBJ design are explained in Section 6. The last section gives a perspective review of the future for SSBJ development.

2. Historical background

The illustration in Fig. 1 shows the progress of supersonic aircraft. There had been a boom in supersonic aircraft since the first flight of the X-1 in 1947; however, they were limited to military applications. Three projects gave birth to supersonic civil transportation in the 1960s. The U.S.

Supersonic Transport (SST) program was cancelled in 1971 as a result of the economic feasibility, sonic booms and environmental issues. The Russian Tu-144 (Fig. 2) was first to achieve flight but spanned only several years of service because of cabin noise, economic inefficiency, and so on. The British/French Concorde (Fig. 3), on the other hand, experienced 27 service years until 2003 [15].

Although there has been a supersonic stagnation for decades, research on supersonic transport has never stopped. Based on the failures of the previous SST program, NASA was given the responsibility to establish the technology base for a viable supersonic cruise aeroplane. As part of the effort, the Supersonic Cruise Research (SCR) program was carried out from 1971 to 1981. The Variable Cycle Engine (VCE) program, a propulsion offshoot of SCR, was conducted from 1976 to 1981 to study the promising VCE concepts. Feasibility studies for the next-generation SST were initiated in the late 1980s. The High Speed Research (HSR) program began by NASA in 1989, including in-depth studies from 1995 with Tu-144 test flights. The High Speed Civil Transport (HSCT) program, the focus of HSR program, aimed at developing a 300-passenger, Mach 2.4 supersonic airliner. The program terminated in 1999 on account of environmental challenges and budget problems. The Quiet Supersonic Platform (QSP) conducted by DARPA from 2000 to 2006, aimed at developing a low-boom (0.3 psf) supersonic aircraft both for military and civil applications.

In Europe, the next-generation supersonic research program was initiated in 1994 but was stopped in the same period as the HSR program because Europe turned to a large aeroplane. HIgh Speed AirCraft (HISAC), also called ‘environmentally friendly HIgh Speed AirCraft’, was conducted from 2005 to 2009 to research the technology base of a small-size environmentally friendly supersonic transport.

Japan Aerospace Exploration Agency (JAXA) initiated a scaled supersonic experimental aeroplane project named NEXST (National Experimental Supersonic Transport) project [16] in 1996 so as to establish advanced design technologies for the next-generation SST. The program ended in 2007. The Silent Supersonic Technology Demonstration (S3TD) program [17] started in 2006 to validate MDO design tools and demonstrate the silent supersonic aircraft concept. The Drop test for Simplified Evaluation of Non-symmetrically Distributed sonic boom (D-SEND) project [18, 19] started in 2007 to drop models from balloons to validate the sonic boom mitigation technology.

Through several decades' of studies, it is apparent that a small-size supersonic transport could be the first step into a new supersonic era. The increasingly stringent noise requirements have created the need for the supersonic jet to the quiet supersonic jet (QSJ) program [20].

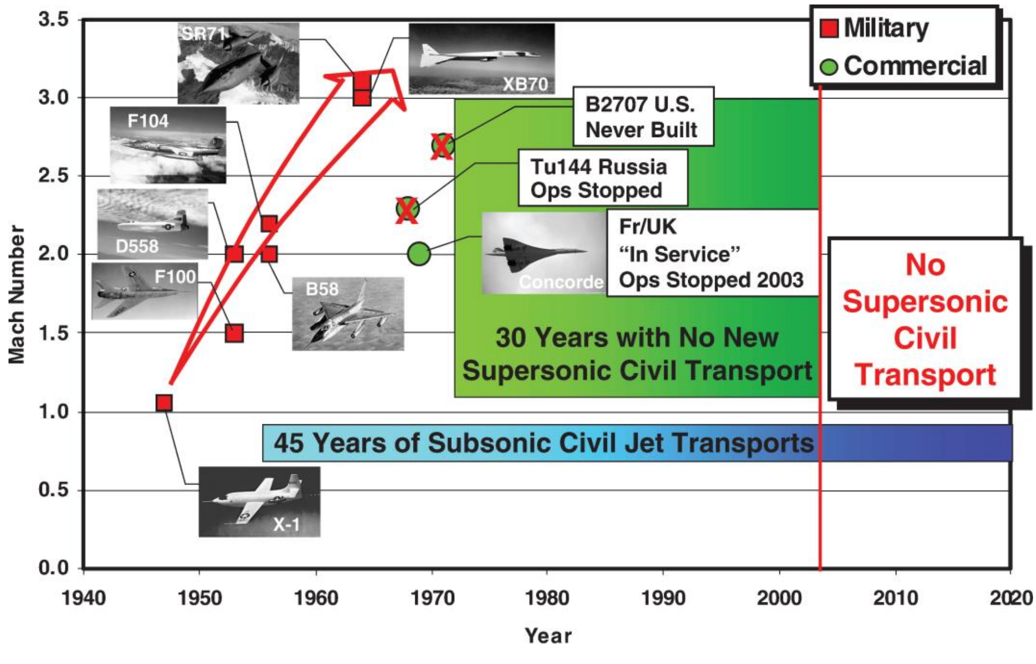


Fig. 1. Supersonic aircraft progress (Source: [3])

Fig. 2. Tu-144 (Source: [21])

Fig. 3. Concorde (Source: [22])

3. Market analysis

The potential consumers for SSBJs include corporate flight departments, government agencies, private individuals, charter companies and fractional companies.

The passengers' willingness to pay and the service quality they demand is qualitatively presented in Fig. 4. The figure potentially indicates a small size supersonic aircraft market gap in the overall market. It indicates that the SSBJ may appeal to frequent business travelers (the 'Road Warriors') and a portion of business jet users, which together take up about a 10% market share [23].

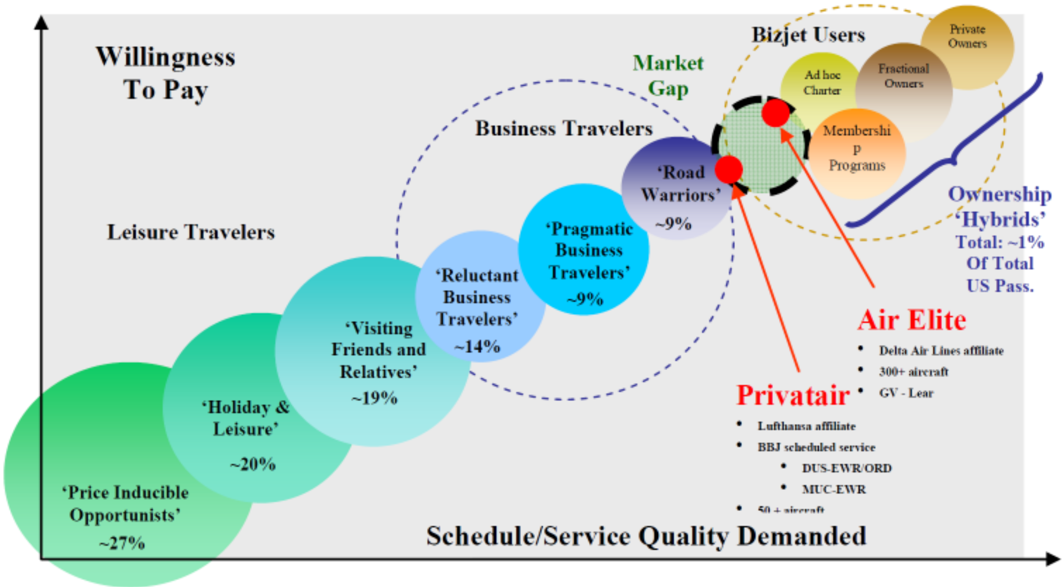


Fig. 4. Potential size of the supersonic passenger market (Source: [23])

In 1999, Meridian International Research carried out a comprehensive study [24] into the potential market for a future SSBJ. The result indicates that for a small US$50-100m SSBJ, a market of 250-400 units exists over the next 10-20 years.

In 2003, Gulfstream studied the potential demand for small QSJs with two different methods. The bottom-up approach predicted at least 180 units market demand, while, the analytical projection method indicated a possible 350 aircraft, as shown in Fig. 5, over the period of 2013-2022 [3].

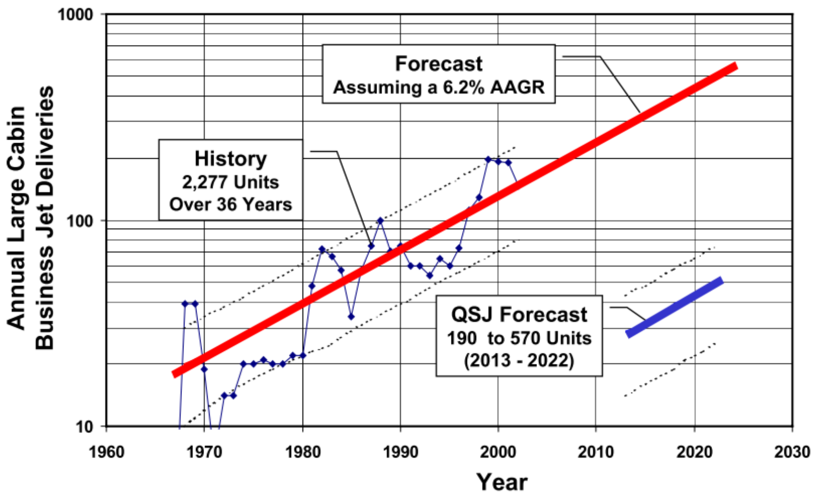


Fig. 5. Gulfstream analytical projection method for QSJ market forecast (Source: [3])

A report released by Aerion Corporation in 2005 showed a market for between 220 and 260 Aerion SSBJs over a 10-year period, about 20% of which comes from the fractional companies. Aerion also noted that production over a 20-year program life could exceed 500 units [25].

Teal Group believes that if business jet deliveries keep ramping up above $30 billion annually, there would be an ironclad case to develop a long-awaited SSBJ [26]. In a study in 2007, Teal Group predicts a market of 400 SSBJs over 20 years [27].

A recent study [1] summarizes that the market demand for SSBJ is around 20 units per year. However, sufficient demand is neither certain nor verifiable. It is also noted that there are various operational modes for SSBJ class aircraft, but a one-dimensional market will not suffice to realize a growth. Ideally, small supersonic aircraft could make use of the trends introduced by transonic business jets to allow for fractional companies, cargo services, or military and government organizations.

4. Interested companies and organizations

A review has studied the SSBJ research from 1963 to 1995 [28]. During the three decades, there have been a total of 22 activities (six university studies, eight industry studies and eight NASA studies) on the subject of SSBJ. A chronological list of these studies is presented in Table 1.

Table 1. Chronological listing of SSBJ studies from 1963 to 1995 (Source: [28])

Year	Study	Mach No.	Range (nm)	TOGW (t)	PAX+ Crew	Wing Planform	Engine No.	Fuselage Length (m)	Cabin Height (m)	Cruise ΔP_0 (psf)
1963	U-1	3.0	3500	3.8	4+2	Trapazoidal	2	12.2	1.22	-
1965	I-1	2.0	3000	20.0	12+2	Delta-ogive	2	25.5	1.55	-
1967	U-2	2.2	3000	31.8 31.3	10+2	Delta unswept trapaz	4/2	27.3 25.9	1.83	1.5
1967	U-3	2.0	3300	28.6	9+2	Variable sweep	4	25.9	1.46	-
1971	I-2	-	2580	46.9	10+2	Delta	-	-	-	-
1977	N-1	2.2	3200	33.6 36.3	8+2	Arrow	2	32.6	1.74	1.0
1977	N-2	2.4	3250	25.4	0+2	Arrow	2	28.5	1.37	-
1980	N-3	2.7	3200	42.5	8/10+2	Arrow	2/3/4	29.3	1.65	-
1981	N-4	2.7	3200	-	8+2	-	-	-	1.65	0.5
1981 **1985**	I-3	2.0- 2.2	4000+	45.4 60.8	8+3 14+2	Arrow; Cranked arrow	2/3/4	30.5 39.0	1.83	1.3
1981	N-5	2.7	3200	29.0	8+2	Arrow	2	31.4	1.77	0.9
1983	N-6	2.3	3350	23.1	8+1	Arrow	2	31.4	1.46	0.9
1984	N-7	2.0	3500	29.3	8+2	Variable sweep	2	32.6	1.62	1.0
1986	N-8	2.0	3622	27.9	8+2	Arrow	2	31.4	1.74	0.9
1987	I-4	2.0	4000+	-	-	-	-	31.4	1.74	-
1988	I-5	1.5	3500+	45.3	8+2	Delta ogive	4	38.1	1.83	0.6
1988 **1990**	I-6	1.5 2.0	4000+	36.3	10+2 12+2	Cranked delta arrow	3 4	30.5	-	-
1990	U-4	2.2- 2.5	4980 4750	47.4 58.2	8+2 9+2	Arrow; Variable sweep	3/4	33.5 41.1	-	-
1992	U-5	-	-	-	-	-	-	-	-	-
1993	I-7	2.0	4600	48.1	10+2	Cranked arrow	2	34.7	-	-
1993	U-6	2.2	5000	48.5	7+2	Delta	2	32.6	1.89	-
1995	I-8	1.8	3350	29.9	8/10+2	Cranked arrow	4	27.7	1.83	0.4

4.1 Aerion Corporation

The Aerion Corporation [29] of Reno, Nevada, was formed in 2002 to introduce a practical and efficient SSBJ. Its idea is to develop a twin-engine SSBJ configuration named AS1 [30], shown in Fig.

6(a). The concept utilises the already certified P&W JT8D engine to minimize the design risk. The Aerion SSBJ's key technology, supersonic natural laminar flow, has been verified in flights by NASA and in transonic wind tunnels. However, Aerion decided to make the jet bigger and reduce emissions from the engines. The concept was changed to the triple-engine SSBJ configuration named AS2, as illustrated in Fig. 6(b).

In 2012, Aerion acquired Desktop Aeronautics (renaming it Aerion Technology) to develop its specialized codes for analysing supersonic airflows and optimizing airframes. In November 2015, Aerion received an order from fractional jet supplier Flexjet for 20 Aerion AS2 supersonic jets worth $2.4 bn. Aerion is now cooperating with INAIRVATION to develop innovative cabin interiors and working with Airbus to manufacture these jets. The AS2 jet is expected in to make its first flight in 2021 [31].

(a). Aerion Corporation AS1

(b). Aerion Corporation AS2

Fig. 6. Aerion Corporation SSBJ concepts (Source: [29])

4.2 Supersonic Aerospace International

Supersonic Aerospace International (SAI) [32], based in Las Vegas, was founded in 2000 to create a Quiet Supersonic Transport (QSST) for the 21st century. The central feature is the ‘quiet supersonic’ technology that will ensure a low boom signature to make flights over land. The QSST-X (Fig. 7) features an advanced double delta wing design, which is similar to Concorde’s ogee-delta wing, but what is unique is the inverted V-tail. Lockheed Martin found that the inverted V-tail is beneficial and conducive to achieving the ‘virtually boomless’ design as it restricts the sonic signature coming off of the back of the aircraft. The broad distribution of lift-generating surfaces is another key to constraining sonic boom.

Based on a preliminary study and business case model, the QSST-X would be viable at US$130-140 million in the recent report [33]. To date, SAI and Lockheed Martin have invested over US$70 million in research and development on the QSST-X program [34].

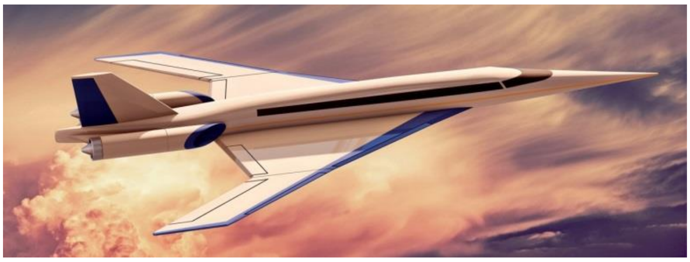
Fig. 7. Supersonic Aerospace International QSST-X (Source: [32])

4.3 Spike Aerospace

Spike Aerospace [35] is a Boston-based company launched in 2013. The company is developing the high-level conceptual design of supersonic aircraft for pleasure and business. In the first design phase, the company proposed an SSBJ concept as shown in Fig. 8(a). During the second phase, the Spike S-512 supersonic jet was updated to offer quiet supersonic flight. The wing was noticeably changed to a modified delta wing, featuring a highly swept inboard wing with a slender outboard wing section as shown in Fig. 8(b). At its full cruise speed of Mach 1.6, the sonic boom is expected to be less than 70 PLdB. With a luxurious multiplex digital cabin, as presented in Fig. 9, the noise level in the cabin will reduce by 20dB.

In January 2016, Spike Aerospace announced its partnership with Aernnova in developing and validating the major structural systems. Recently, Spike Aerospace started evaluating several engine options to seek low to medium by-pass ratio engines with approximately 20,000 lbs (88.9 kN) sea-level thrust. The S-512 is estimated to cost US$ 100 million and expected to be delivered in 2023 [36].

(a). First design of S-512



(b). Second design of S-512

Fig. 8. Spike Aerospace S-512 supersonic jet (Source: [35])

Fig. 9. Multiplex Digital Cabin of Spike S-512 supersonic jet (Source: [35])

4.4 HyperMach Aerospace

HyperMach Aerospace [37], based in Los Angeles, formally came into being in 2008. It develops the concept of SonicStar (Fig. 10), which is said to be able to fly at Mach 4.0 with the sonic boom intensity as low as 0.25lb/ft^2. The company developed a hybrid engine technology to reduce emissions and noise.

The hybrid electric turbine engines for SonicStar are being developed by HyperMach's sister company

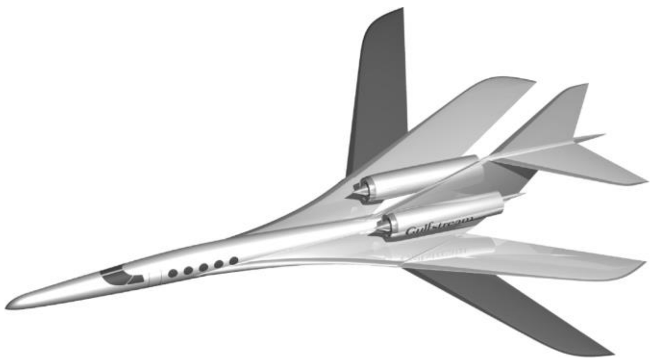
SonicBlue. Aeronautical Testing Services, Inc., Design By Analysis, Inc. and Eagle Harbor Technologies all have signed agreements with HyperMach to develop the SonicStar supersonic transport. HyperMach is currently seeking investment and preparing for the first flight in 2021 [31].

Fig. 10. HyperMach Aerospace SonicStar (Source: [31])

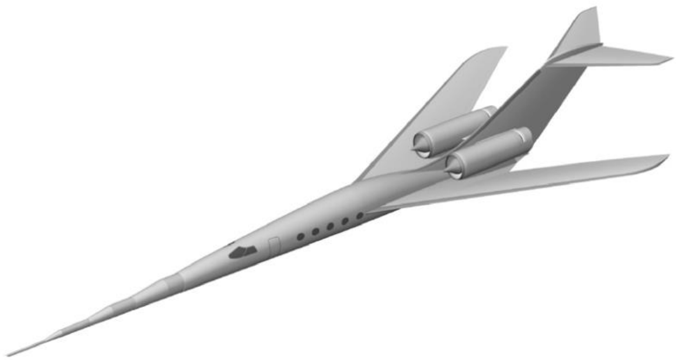
4.5 Gulfstream Aerospace

Gulfstream Aerospace has long been interested in the feasibility of developing a multi-use supersonic aircraft appropriate to both civil and military roles. Gulfstream has sponsored a group of technical resources on the supersonic transport study. The Quiet Supersonic Jet (QSJ) is the result of these studies, as shown in Fig. 11(a) and (b). Its most notable features include a nose spike device for sonic boom reduction and a swing-wing configuration to balance supersonic cruise and low-speed performance.

Gulfstream Aerospace has worked with NASA to take flight trials on the F-15 to validate the feasibility of the 'Quiet Spike'. The near-field shock signatures were investigated within the flight envelope of Mach 1.8 and 45,000 feet. The 'Quiet Spike' can mitigate sonic boom intensity whilst maintaining a suitable aircraft shape.



(a). Variable sweep concept (Source: [3])



(b). Quiet spike concept (Source: [38])

Fig. 11. Gulfstream Aerospace QSJ concepts

4.6 Sukhoi

The Sukhoi Design Bureau of Moscow and Gulfstream Aerospace started their cooperation in developing a small SSBJ in the early 1990s. The new configuration named S-21 is shown in Fig. 12. The S-21 is able to cruise at Mach 2+ propelled by three Aviadvigatel D-21A1 turbofans. Nevertheless, this partnership was ended by Gulfstream as a result of the uncertain market demand.

Sukhoi continued the design and research work on S-21. There is still an ongoing ‘supersonic business jet’ project on its website [39]. Sukhoi displayed a concept for a quiet SSBJ at the MAKS Air Show in 2013. The model features a double delta wing with significant dihedral for sonic boom mitigation, as presented in Fig. 13.

The Central Aerohydrodynamic Institute (TsAGI), in cooperation with Sukhoi and aircraft engine manufacturer NPO Saturn, is developing the preliminary design of a quiet SSBJ. A conceptual drawing of this configuration is shown in Fig. 14. The aircraft features a long, pointed nose to alleviate the sonic boom, four shielded engines to decrease noise, and long thin wings to increase the lift to drag ratio [40].

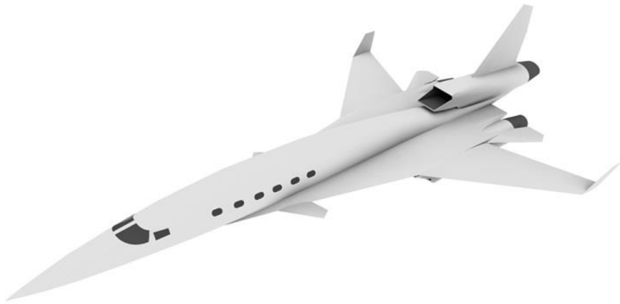


Fig. 12. Sukhoi-Gulfstream S-21 SSBJ (Source: [41])

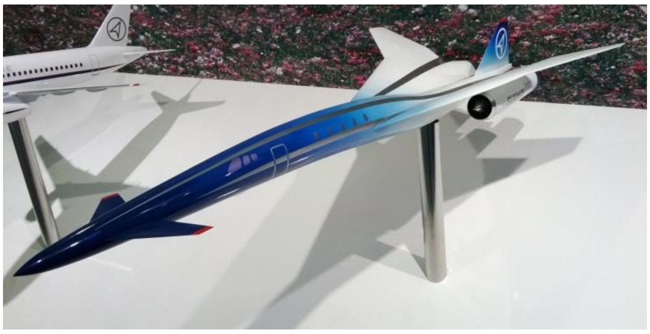


Fig. 13. Sukhoi SSBJ model (Source: [41])

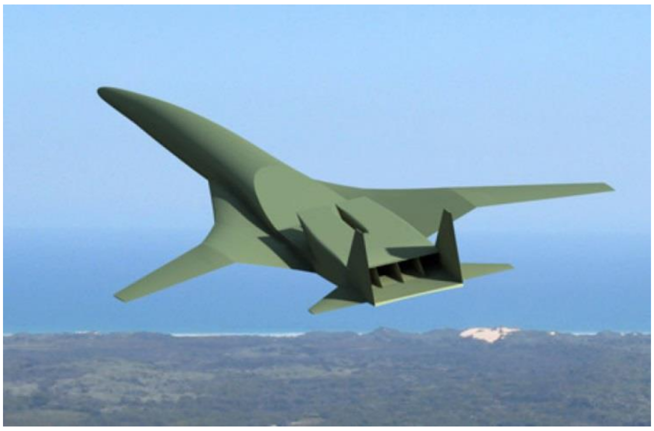
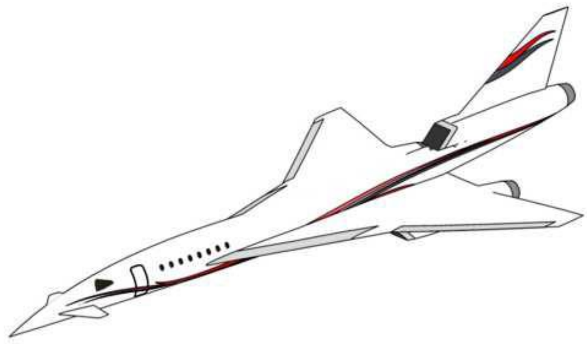


Fig. 14. TsAGI SSBJ concept (Source: [40])

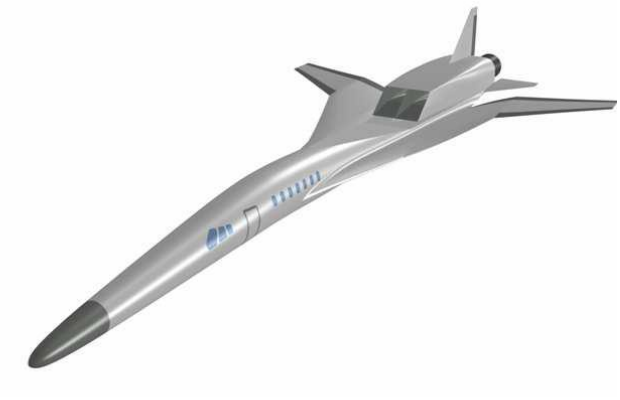
4.7 HISAC

The 'Environmentally Friendly High Speed Aircraft' (HISAC) research program is an ambitious European 'integrated project'. 37 partners from 13 countries are involved in the consortium of industry and academia. The HISAC project aims to explore the feasible technical solutions through an MDO approach under high environmental constraints in terms of noise, emissions and sonic boom. Under the same common requirements, three configuration families are concluded by different teams, as shown in Fig. 15. The detailed description of these configurations can be found in Ref. [42].



(a). HISAC-A Low Noise configuration

(b). HISAC-B1 Long Range configuration



(c). HISAC-D Low Boom configuration

Fig. 15. HISAC SSBJ conceptual design cases (Source: [42])

4.8 NASA

NASA has conducted research on supersonic civil transport for nearly 60 years. There has been research on methodologies, wind tunnel tests, flight trails, etc. Technologies (such as quiet spike, supersonic laminar flow, etc.) are being matured under the N+ projects.

Recently, NASA announced its intention to invest $20 million in Lockheed Martin to develop a quiet supersonic X-plane (Fig. 16) for Quiet Supersonic Technology (QueSST) [43]. This delta-wing configuration features a long nose to mitigate sonic boom, several lifting surfaces (canard, wing, mini T-tail and conventional horizontal tail) to separate shock waves [34]. The upward-facing cockpit indicates an enhanced forward vision system. The supersonic X-plane team is expected to start building in 2019, make its first flight in 2020 and then continue sonic boom flight trails in southern California for several years [44].

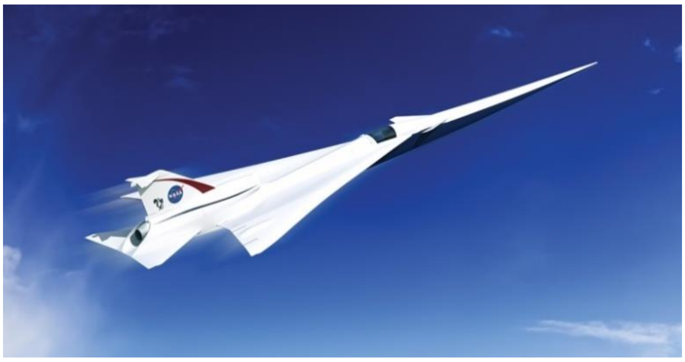


Fig. 16. NASA low boom flight demonstration Quiet Supersonic X-plane (Source: [43])

4.9 JAXA

Japan Aerospace Exploration Agency (JAXA) has been working on the next generation SST for a long time. The SST research and development roadmap at JAXA is shown in Fig. 17. JAXA performed NEXST Project, D-SEND Project as well as S3TD Project to study the feasibility of low-drag low-boom supersonic transport.

JAXA cooperates with the SKY Aerospace Institute on a trial design for SSBJ concept [45], as shown in Fig. 18. Technological achievements in previous projects have been applied in the design. For example, the cranked arrow wing uses natural laminar flow technology that was demonstrated in the NEXST project. An automatic MDO system CAPAS [46] developed during the S3TD project was used in the design of SSBJ-M. The non-symmetrical fuselage comes from the D-SEND project to mitigate sonic boom.

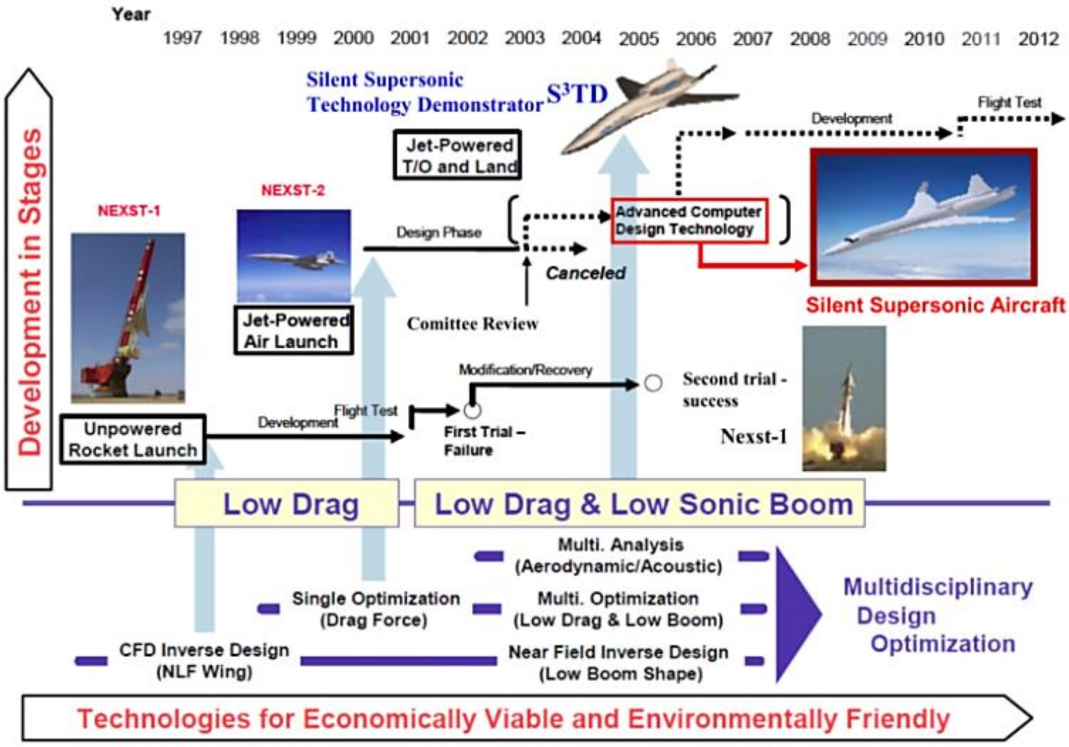


Fig. 17. Roadmap of SST R&D at JAXA (Source: [47])

Fig. 18. JAXA SSBJ-M conceptual design (Source: [36])

4.10 Cranfield University

Cranfield University is a graduate university with an international reputation in aerospace research. The design of the E-5 Neutrino Supersonic Business Jet (Fig. 19) was carried out by 15 academic staff and team of 30 students over a period of seven months. The scope of the study is to provide a complete review of the issues relating to the design of supersonic business jets – the E-5 being a focal case study [48].

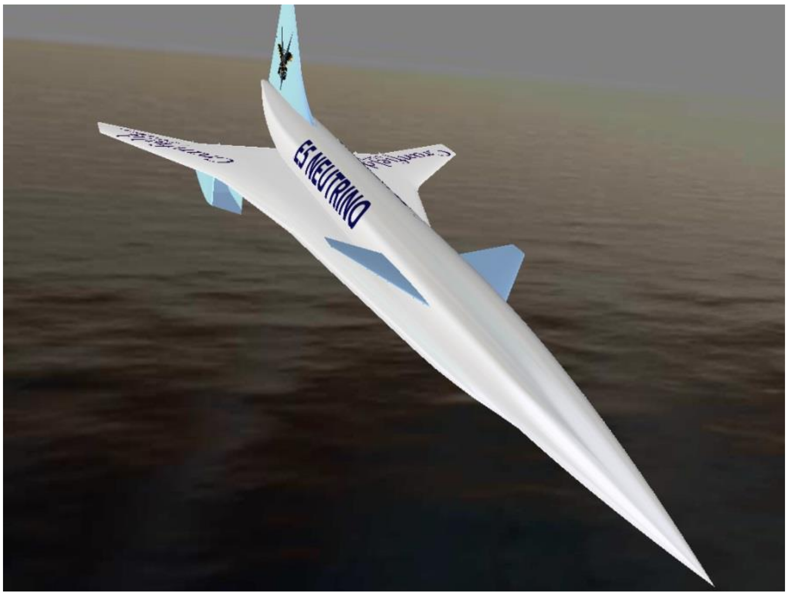


Fig. 19. Cranfield University E-5 Neutrino Supersonic Business Jet (Source: [48])

4.11 Summary

A summary of the SSBJ concepts developed by the above companies and organizations in recent years are presented in Table 2.

Table 2. Summary of recent SSBJ designs

Year	SSBJ designs	Range (nm)	Mach No.	PAX.	Length (m)	Span (m)	Max. thrust (kN)	MTOW (t)	Noise	Cruise ΔP_0 (psf)
1990s	S-21	2715	1.4	6-10	37.9	19.9	220.6	51.8	-	-
2003	Gulfstream	4800	1.8	8-14	42.7	-	-	45.4	Stage IV-10dB	0.15
2006	Cranfield E-5	5700	1.8	6	43.6	16.0	197.2	45.5	-	-
2009	SAI QSST	4000	1.6	8-12	40.3	19.2	294.0	69.4	Stage IV	0.30
2009	HISAC-A	4000	1.6	8	36.8	18.5	220.0	51.1	Stage IV-10dB	0.94
2009	HISAC–B1	5000	1.6	8	41.6	24.0	313.5	60.5	Stage III-5dB	1.56
2009	HISAC–C	4000	1.8	8	40.9	19.1	292.6	53.3	Stage IV-2.5dB	0.42
2009	Hawker /Raytheon [49]	5000	1.8	6-8	50.4	21.0	226.0	54.1	Stage IV	0.40
2010	Aerion AS2	4000	1.5	8-10	51.8	18.6	174.4	54.9	Stage IV	-
2010	Uni. Stanford	4000	1.6	6-8	38.1	20.0	-	43.1	-	0.42
2011	SonicStar	6800	4.0	10-20	68.8	22.6	486.3	77.9	Stage IV	0.25
2013	Spike S-512	4000	1.6	12-18	37.0	17.7	177.8	52.2	-	70PLdB
2013	JAXA SSBJ-M	3500	1.6	10	39.6	16.8	140	36	Stage IV	0.96
2016	NASA X-plane	-	1.42	1	28.7	10.0	60.0	10.2	-	75PLdB

5. Mission Requirements

5.1 Range Capability

Supersonic transport aircraft are preferred to operate over water to minimize the sonic boom impact on the ground. Thus, Trans-Atlantic and Trans-Pacific routes can be evaluated to find a minimum and maximum range value for the SSBJ. A non-stop trans-Atlantic flight is approximate 3000-3500 nm, whereas a non-stop route traversing the Pacific Ocean is 5000-6000 nm (Fig. 20). The lower boundary of an SSBJ’s range capability is to cross the Atlantic Ocean without stops, which also enables the Trans-Pacific flight with just one stop for refuelling. In an analysis for supersonic flight routing, 250 origin-destination city pairs regarding total premium ticket revenue in 2012 were studied. For the design range between 4000 nm and 5000 nm, 76% of all the flight paths contain no intermediate overland segment [50].

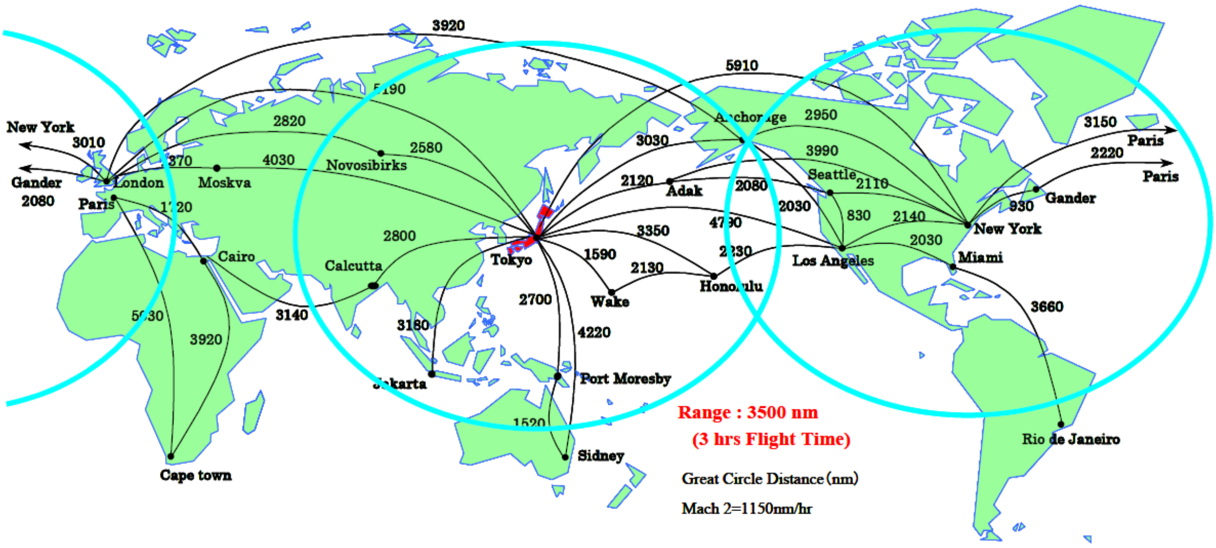


Fig. 20. Great cycle distance between major cities (Source: [51])

Fuel fraction is another factor that would restrict the range capability. The derived Breguet-Range equation definition is as below:

$$R = \frac{(Ma \times a)}{SFC} \times \frac{L}{D} \times \ln\left(\frac{W_{TO}}{W_{LD}}\right) \tag{1}$$

$$W_{LD} = W_{TO} - W_F \tag{2}$$

where a=speed of sound, SFC=specific fuel consumption, W_{TO}=take-off weight, W_{LD}=landing weight, W_F=fuel weight.

When values of Ma=1.6, a=295 m/s, L/D=7, and SFC=1.0/h are applied, the fuel fraction for a range of 3500 nm is W_F/W_{TO}=42%. As plotted in Fig. 21, the fraction of 42% is well within reach for typical supersonic transport. Improvement of L/D from 7 to 8 would achieve a range improvement of 15% (4000 nm), or L/D=9, 30% (4500 nm). A range improvement from 3500 nm to 5000 nm is considered feasible through an L/D improvement and an airframe weight reduction [51].

Current SSBJ designs are considered to have the capability of carrying fuel fraction of about 50% of maximum take-off weight. It is obvious through the calculation that a long range is possible with a high fuel fraction, high L/D, and good engine performance. Therefore, an SSBJ is likely to have a range target in the region of 3500-6000 nm. A compromise would be possible between 4000 nm and 4500 nm [52].

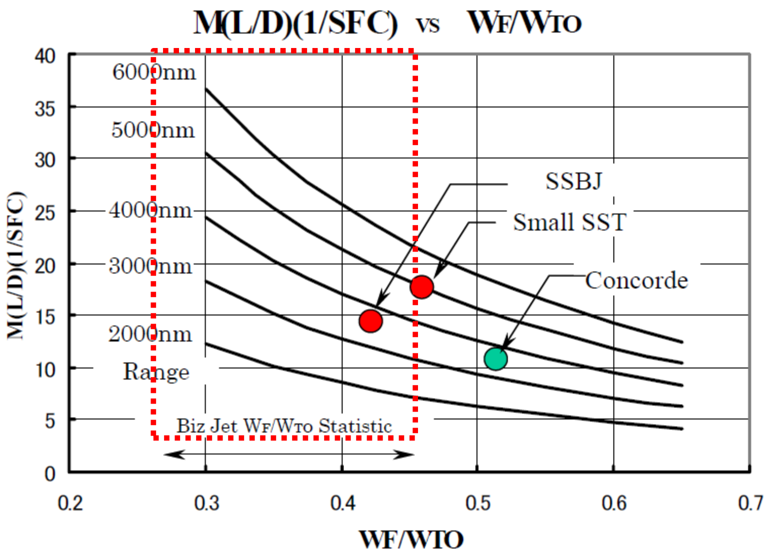


Fig. 21. Range capability prospect (Source: [51])

5.2 Mach number

In the supersonic regime, the technical challenges will increase as Mach number increases, as indicated in Fig. 22. For a civil business vehicle, it is not hard to set an upper boundary of Mach 2.0, considering the challenge of thermal protection. Such a limit also contains propulsion installation complexity and avoids significant aerodynamic heating in the propulsion system [3]. Besides, common aeronautical materials cannot be used largely above Ma 2.0, which is discussed in Section 6.5.2.

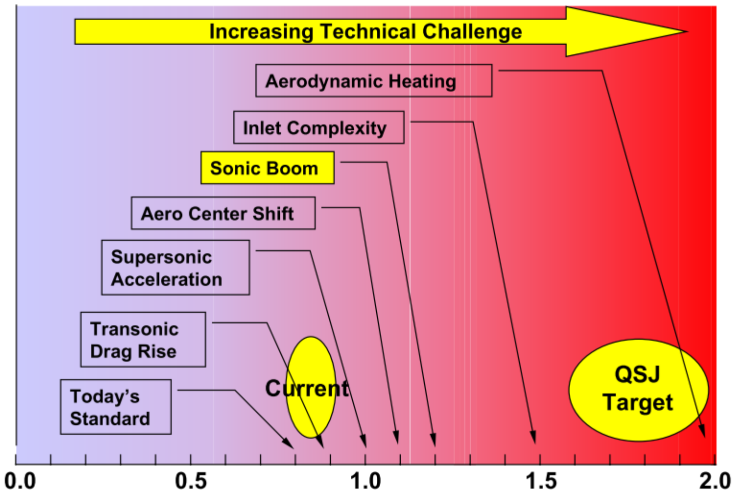


Fig. 22. Supersonic speed challenges (Source: [3])

It is still uncertain whether the SSBJ will be a competitor to current subsonic business jets or help fill in the blanks in the business market. Supersonic travel should maintain its time advantage whether for non-stop Trans-Atlantic routes or for one-stop Trans-Pacific routes. For an SSBJ of 4000 nm, the time saving for non-stop Trans-Atlantic routes and for one-hour-stop Trans-Pacific routes can be seen in Fig. 23.

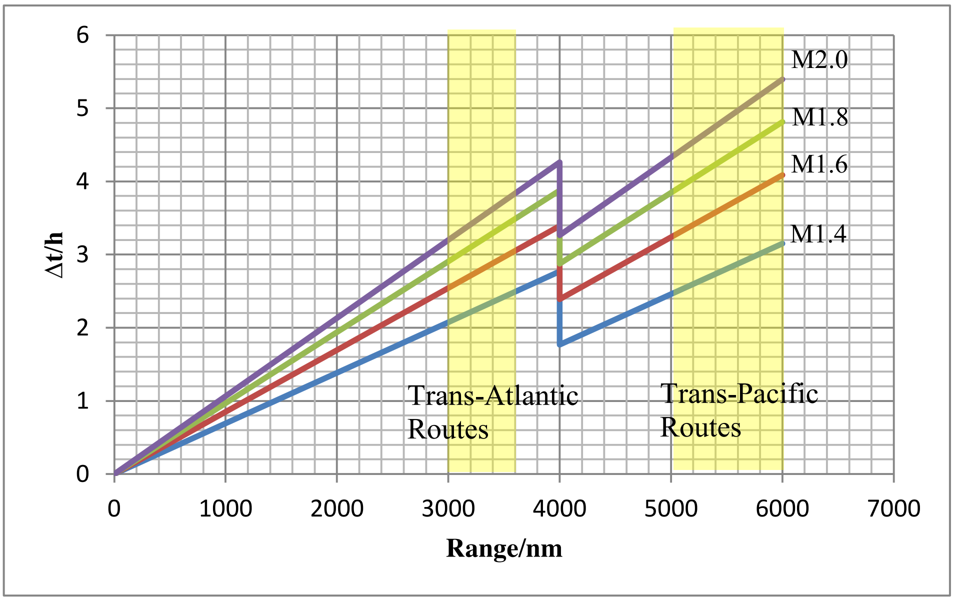


Fig. 23. Time advantage of supersonic travel compared with subsonic travel

The trans-Atlantic route, such as London to New York is in great demand for business transports.

Operating SSBJs on this route would make a one-day return possible, as indicated in Fig. 24. Thus, it would provide a clear time advantage compared to the subsonic airline service with an overnight stay [51].

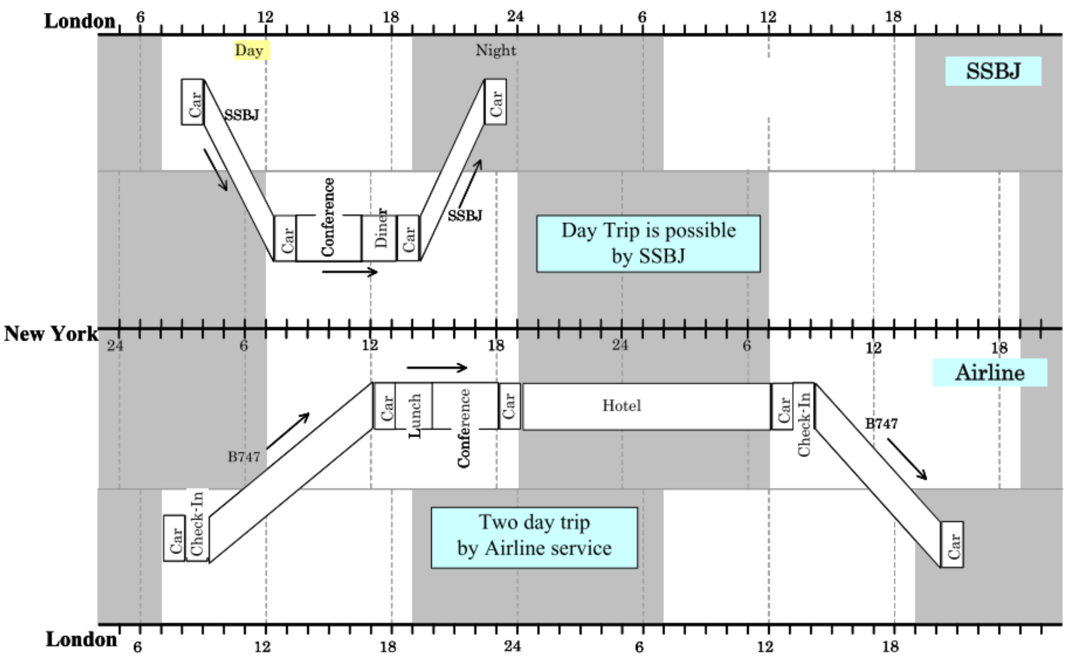


Fig. 24. Comparison of schedules at Trans-Atlantic Route (Source: [51])

Jet lag occurs when the time zone does not line up with the body's internal clock. Suffering from jet lag chronically can lead to a suppressed immune system, chronic fatigue and memory issues. For business travel shown in Fig. 24, travelers can come back to the original time zone instead of adapting to the new one. Supersonic travel may eliminate jet lag as the passengers' internal clock will not be disturbed too much [53]. Passengers on Concorde reported less jet lag than on other transatlantic flights [54].

The target Mach number is likely to be within Mach 1.4 and 2.0. The final decision should be made considering the sensitive relationship between speed, range, routes, and sonic boom.

5.3 Flight altitude

5.3.1 High-altitude emissions

Supersonic vehicles cruise at a higher altitude than subsonic vehicles, therefore, have a greater potential to deplete the ozone layer. UIUC studied the impact of a fleet of SSBJs' emission on the total column ozone [55]. The results indicate that the crossover point for ozone depletion is around 14.5 km, whatever the combinations of total fuel burn (Mlbs/day) and emission indices (E.I.). Though there would be an ozone depletion effect above 14.5 km, the impact is less than a few hundredths of a percent near the crossover point, which is likely imperceptible. Thus for emissions reasons, the flight altitude for SSBJs is preferred to be no more than 17 km.

5.3.2 High-altitude radiation

Cosmic radiation is a serious concern at high altitude. The Earth's atmosphere provides an effective shielding against cosmic radiation at sea level. However, at 20 km, the shielding level for the primary proton flux drops to 50% of the ground value, the alpha particle flux to 15%, and the heavy ion flux to about 3% or less [56]. In 1976, at the time Concorde came into service, cosmic radiation was identified as a potential risk. However, a study carried out by the British Airways Medical Service in the 1980s showed that the maximum exposures are 10.79-17.41 millisievert (mSv) per year for the airline crew members and passengers [57]. This figure is well within the International Commission on Radiological Protection (ICRP) recommended limits of 20 mSv per year. A recent study concludes that it is quite rare for the aircrew and passengers to suffer health damage from cosmic radiation [58].

5.3.3 High-altitude operation safety

Cabin depressurization at altitudes higher than 50,000 ft will pose a safety risk to passengers and crew, especially in the case of a rapid decompression. FAR 25.841 requires commercial aircraft to be designed so that occupants will not be exposed to a cabin pressure altitude that exceeds 25,000 ft for more than 2 min or a pressure altitude of 40,000 ft for any duration. This is a difficult standard to meet for commercial supersonic aircraft cruising at altitudes well in excess of 40,000 ft. Even if self-healing technologies cannot seal leaks completely, they reduce the leak rate and provide extra time for an emergency descent. An automatic emergency descent mode for aircraft flight control systems triggered by unexpected cabin pressure loss is necessary to meet safety standards [2].

The higher the supersonic vehicle cruise, the less the supersonic drag will be. There would be less dynamic pressure on the structure. However, there is a ceiling for the flight to limit the impact of emissions, reduce the cosmic radiation on the crew and passengers, and operation safety, especially when a fleet of supersonic vehicles operate in the stratosphere. Here, the cruise ceiling for an SSBJ is suggested to be 17 km.

5.4 Seating capacity

According to the Seebass-George-Darden (SGD) theory, the lift together with the aircraft volume directly affects the intensity of the sonic boom. The number of passengers (representing payload weight) has a significant effect on the cabin volume as indicated in Fig. 25. Thus, the sonic boom intensity is very sensitive to the number of passengers.

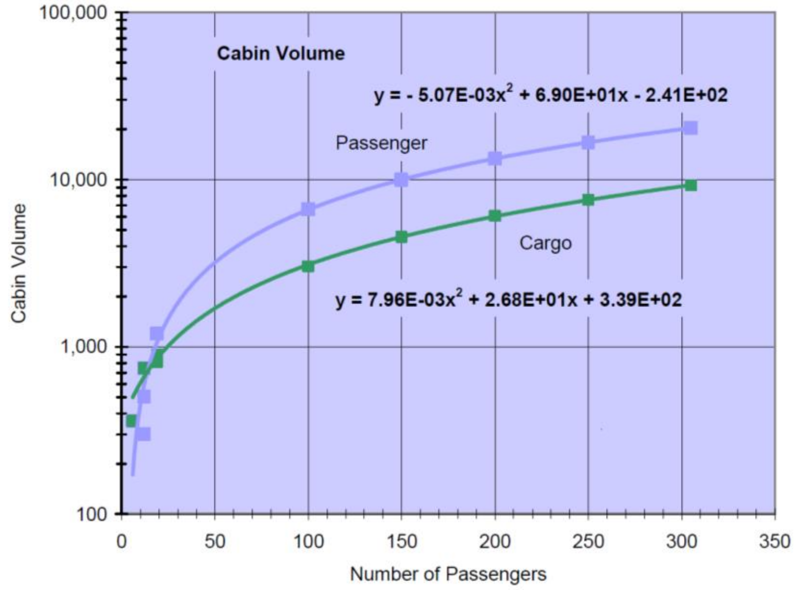


Fig. 25. Cabin volume versus number of passengers for supersonic vehicles (Source: [52])

A survey by the German Aerospace Centre (DLR) [1] among business aviation decision makers shows that 6 seats are sufficient for more than 80% of private long range flights, 7-9 seats are deemed to be enough for most of these operations. In the study, it is concluded that a seating capacity of 10-13 is required, with a minimum of 7-9. The MTOM of a 10-passenger SSBJ is about 50,000 kg, with a payload fraction of 2% [48]. Though, this is a quite low payload fraction.

5.5 Environmental concerns

5.5.1 Global environment

Supersonic flights are usually at higher altitude, deep in the stratosphere, creating a larger impact on the atmosphere and climate compared to subsonic flights. Emissions from supersonic aircraft that would affect the atmospheric are oxides of nitrogen (NO_x) and water vapour. Main concern about the global environment is the potential for altering the composition of the atmosphere, particularly the ozone layer, which would affect the climate significantly.

NASA has studied the potential impact of emissions from SSBJs on stratospheric and tropospheric ozone. In the report, 24 scenarios specified by total fuel burn, emission index of NO_x, and cruise altitudes were evaluated by the UIUC 2D global atmosphere model. The results were obtained from ten-year steady state model simulations. It was found that above a specific altitude the ozone begins to deplete. For the most likely scenario (18 Mlbs/day fuel burn, 20g/kg E.I. of NO_x at 15-17 km), the worst local ozone depletion was 0.038% [55].

SCENIC is an EU-funded project focused on assessing the potential climate impacts caused by fleets of future supersonic aircraft. The project analyses a set of different emission scenarios over a range of fleet size, E.I. of NO_x, cruising altitude, cruising speed, and range. The results confirm previous findings (IPPC, [59] , as shown in Fig. 26) that the emissions of water vapour in the stratosphere are the dominated factor to climate change. The simulation also predicts that a reduction in cruise altitude or speed (from Mach 2.0 to 1.6) helps to reduce ozone destruction and climate impact by approximate 40% [60].

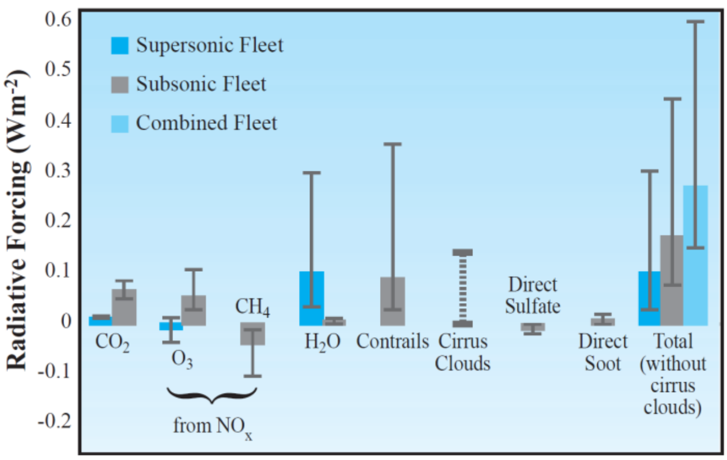


Fig. 26. Radiative forcing from aircraft in 2050 with supersonic fleet (Source: [59])

There have been other studies on the environmental impact of supersonic emissions, including the HSR program [61] and the EU-funded HISAC project [62, 63]. For aeroplanes cruising below the speed of Mach 2, it is concluded that an NO_x index of 15 g NO_x/kg fuel appears satisfactory. From the National Research Council's study [2], the water vapour emission index is referred to about 1400 g water/kg fuel.

5.5.2 Local environment

Design requirement can be found in the regulations (Table 3) to restrict the community noise level during take-off, climb-out, and approach to landing. For subsonic aircraft, U.S. and international standards used to be the Stage 3 requirements. After 2006, Stage 4 (10-dB-quieter to Stage 3 cumulative) has become the new requirement for subsonic jets and transport category large aeroplanes. This newest noise standard is likely to apply to the future supersonic aircraft when operating in the subsonic speed regime [64]. However, to ensure some margin for operational flexibility and technological viability, the noise level of the vehicle should not be higher than current small business jets, as indicated in Fig. 27. This noise requirement can be expressed as a nominally 10-dB-quieter cumulative level relative to Stage 4. Therefore, most of the SSBJ conceptual design cases take Stage 4-10dB as the goal for community noise.

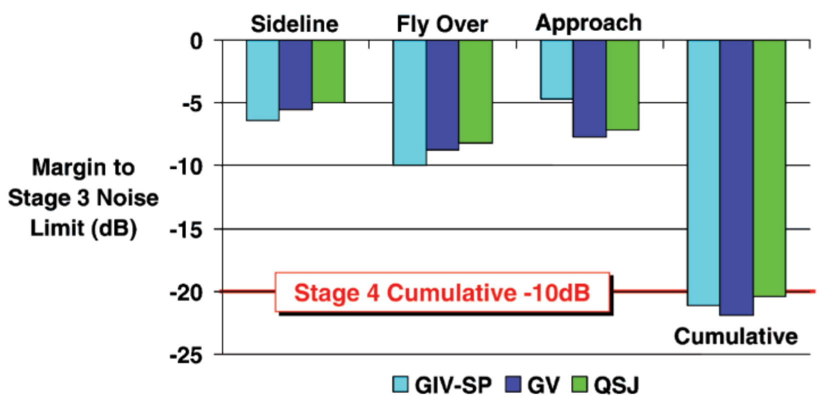


Fig. 27. SSBJ community noise requirements (Source: [3])

5.5.3 Sonic boom intensity

There will be a sonic boom carpet on the ground if an aeroplane flies above the 'cutoff Mach number' (a low supersonic Mach number that the speed over the ground is less than the speed of sound at ground level), as the schematic indicated in Fig. 28. Structures and creatures in the carpet will experience sonic booms.

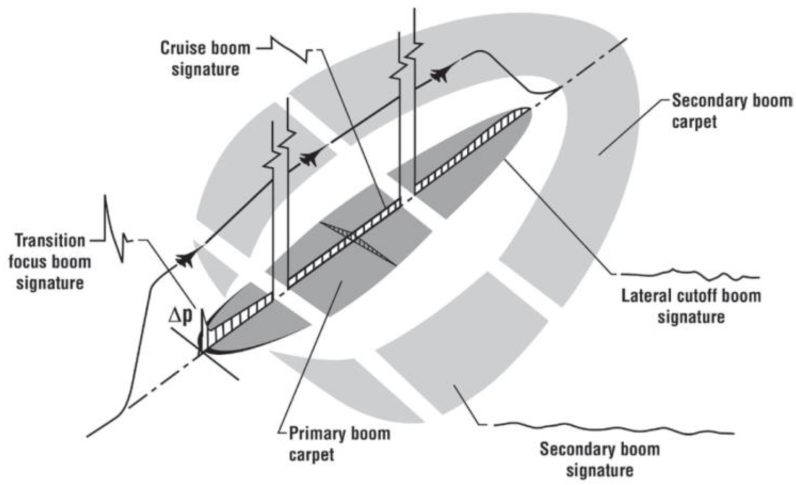


Fig. 28. Schematic of sonic boom ground exposures (Source: [65])

There is no damage to structures or public reaction expected for sonic boom intensity below 1 psf. Noticeable public reaction will appear to a sonic boom for an overpressure of 1.5-2 psf, while minor structural damage may be caused by the overpressure of 2-5 psf. No injury occurs to the human body from sonic booms of 144 psf, generated by a supersonic fly-by at less than 100 ft. Human eardrums will not be damaged below 720 psf. Therefore, the sonic booms generating at cruise altitudes are annoying rather than harmful. Shepherd reported that [66], N-wave overpressures in the region of 0.3-1 psf, depending on the daily flight number, are acceptable to more than 90% of those people tested.

The impact of sonic booms on wildlife and marine life caused concerns as well. Due to significant differences in hearing ability and noise influences on behaviour, the impact on animals resulting from sonic booms varies widely [67]. The sonic boom from aircraft at supersonic speeds is reported to cause lowered reproduction [68]. However, the effect of sonic booms over water was expected to be imperceptible since about 99% of the impinging energy was reflected. Studies showed that sonic booms from normal operations of supersonic aircraft will not harm sea life [65].

Taking the physics of sonic boom into consideration, a small aeroplane is superior to a large aeroplane in terms of sonic boom intensity, as indicated in Fig. 29. As previously mentioned, the weight and size of a supersonic aeroplane have first-order effects on the intensity of the sonic boom strength. For a 100,000 pound (45,359 kg) non-low boom shaped SSBJ, the initial overpressure is approximate 1.3 psf. The signature shaping, coupled with other sonic boom mitigation concepts in Section 6.2.3, might produce a practical way to mitigate the shock intensity to 0.5 psf or less.

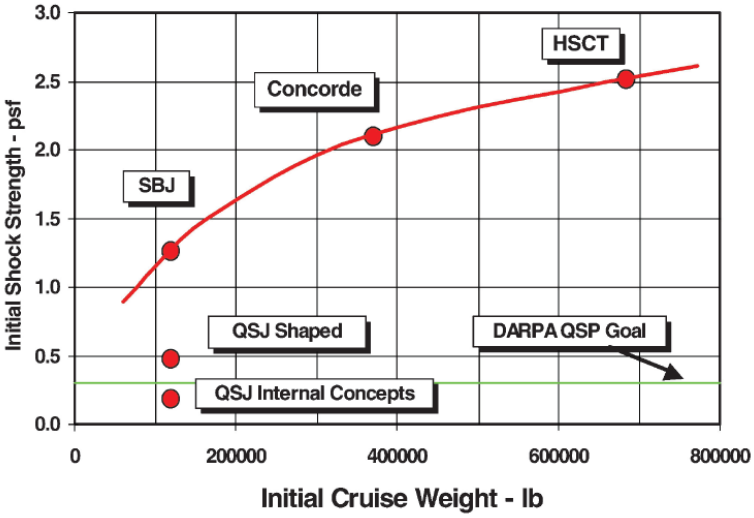


Fig. 29. Initial cruise sonic boom overpressure (Source: [3])

5.6 Airworthiness

After Concorde aroused the public awareness of the sonic boom's power, laws have been enacted by major industrial countries to restrict supersonic flight over land. Environmental regulations relevant to commercial supersonic aircraft are listed in Table 3. Commonly, the sonic boom is not permitted to reach the ground. That is to say, a supersonic aeroplane can cruise up to the cutoff Mach number (about Mach 1.15) which is the case in Germany (LuftVO Section 11). Supersonic civil flights (more than Mach 1.0) are totally banned in the U.S. (FAR Part 91. 817) [1].

In the long run, progress needs to be made toward introducing certifications for supersonic flight over land. The FAA intends to provide guidelines for manufacturers that are interested in designing supersonic aeroplanes. There used to be 'Tentative Airworthiness Standards for Supersonic Transports' during the SST program. Recent update emerged in a policy on the noise limits for future civil supersonic aircraft [64]. Efforts are still required in developing requirements appropriate to supersonic business class aircraft incorporating 21st-century technologies.

Table 3. Environmental regulation applicable to civil supersonic aircraft (Source: [2])

Environmental Issue	Current or Expected Method of Control	International Regulations and Authorities	U.S. Regulation and Authorities
Community noise	Aircraft certification standards, operating restrictions	ICAO (Annex 16, Vol. I)	14 CFR Part 36 and 14 CFR Part 91
Sonic boom	Operating restrictions	ICAO (Resolution A33-7) and LuftVO Section 11	14 CFR Part 91
Climate change	Aircraft certification standards, market-based measures (emissions trading or charges)	United Nations Framework Convention on Climate Changes and ICAO (under Kyoto Protocol, if ratified)	14 CFR Part 34
Ozone depletion	Operating restrictions	Montreal Protocol	Section 615 of the Clean Air Act
Local air quality	Aircraft certification standards	ICAO (Annex 16, Vol. II)	14 CFR Part 34 and 40 CFR Part 87

5.7 Summary

This part analyses the mission requirements for SSBJs. The range capability is a result of routes selection and fuel fraction limitations. The cruise Mach number is closely related to the aerodynamic heat protection and time advantage. Issues with High altitude emissions and cosmic radiation restrict the cruise ceiling of SSBJs. The passenger number is defined considering the sonic boom and market demand. Emission indexes come from the ozone layer simulation and climate change analysis Airport noise level are the newly aviation requirement. The sonic boom intensity is a possible goal to achieve. The design of SSBJs should definitely under specific airworthiness. As a result of the top-level design requirement analysis, likely mission profiles for future SSBJs are listed in Table 4. These values are assumed to be the appropriate initial requirements for environmentally friendly and economically viable small civil supersonic transports.

Table 4. Mission requirements for SSBJs

Requirements	Value
Range	4000-4500 nm
Cruise Mach number	1.4-2.0
Cruise altitude	<17 km
Seating capacity	8-12
Emissions	<15 g NO_x/kg fuel
	~1400 g water/kg fuel
Cumulative airport noise	Stage 4–10dB
Sonic boom intensity	<0.5 psf

6. Technological challenges and solutions

Low drag and low boom are the biggest challenges for an SSBJ. These issues, however, are tightly related to many other aspects, such as wing configuration, body shape, propulsion system, structure, operations, and so on. Design methodologies that can properly predict the aerodynamic coefficients and sonic boom intensity are well worth exploring. Technological issues will be specified in this section and solutions will be addressed.

6.1 Configuration

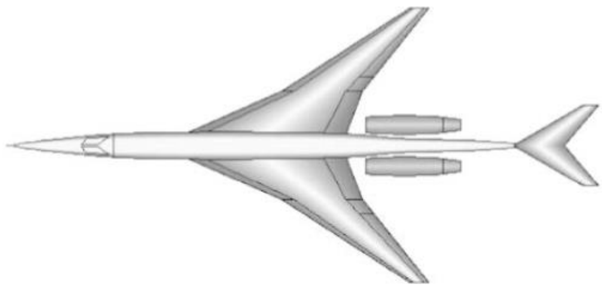
Whilst many researchers have explored a wide range of possible wing geometries, as no supersonic business jet currently exists there is no real data against which these designs could be available. The basic goals for geometry design are to mitigate sonic boom intensity, reduce supersonic wave drag, and provide a comfortable environment for passengers.

6.1.1 Wing shape

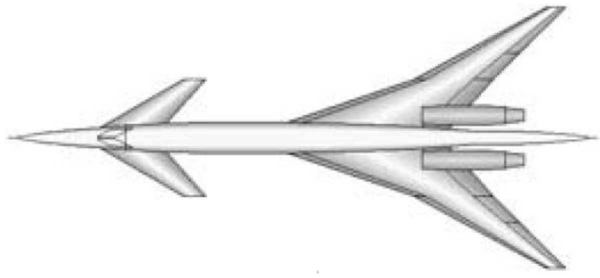
6.1.1.1 Conventional high-sweep wing:

The high-sweep wing, Fig. 30(a), is applied to the supersonic cruise aircraft primarily to reduce the wave drag. Another advantage of this configuration is that, during take-off and landing, at high angles of attack, the vortex produced by the leading edges can help to augment wing lift.

The canard configuration, Fig. 30(b), compared with the aft tail configuration, exhibit of two advantages; lower trim drag and lower sonic boom intensity. The canard contributes to lift compared to a aft tail configuration. Hence the size of the main wing is reduced. The lower lift on the main wing leads to lower trim drag. The canard configuration can potentially mitigate sonic boom through a more uniform equivalent area and lift distribution along the length of the vehicle.



(a) Generic conventional supersonic configuration



(b) Generic canard supersonic configuration

Fig. 30. Various configuration concepts for supersonic aircraft (Source: [69])

6.1.1.2 Variable geometry wing:

The variable geometry wing (Fig. 31) is introduced to improve low-speed performance without compromising high-speed potential.

The variable wing concept could, compared with the fix-wing high-sweep configuration, improve supersonic efficiency, mitigate sonic boom overpressure, result in better subsonic aerodynamic performance, lower noise level and lower take-off and landing distance. A 120,000 lb (54,431 kg) variable geometry wing configuration was reported to achieve a sonic boom overpressure of 0.977 psf, 13% less compared to a constrained highly swept configuration [70]. However, the inefficient wing load paths caused by the pivot leads to a structural weight penalty. The mechanical system challenge and flight control system make the design more complex. Regulations today may not be enough to fully address the difficulties of a variable geometry wing [71].

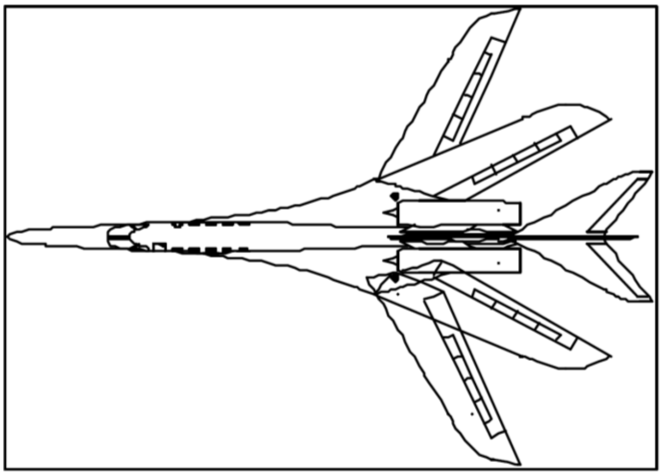


Fig. 31. Variable-geometry wing SSBJ configuration (Source: [71])

6.1.1.3 Supersonic laminar flow wing:

Supersonic laminar flow is regarded as a key technology to improve the aerodynamic efficiency of supersonic transport. The technology is the main characteristic of Aerion Corporation's SSBJ concept, as presented in Fig. 6.

Delta wing configurations cannot maintain extensive laminar flow as a result of adverse pressure gradients and boundary-layer crossflow [72]. The schematic in Fig. 32 indicates the wing shape, airfoil, and pressure distribution of a delta wing compared with the low-sweep laminar wing. The laminar flow wing features a low swept leading edge and sharp-nosed biconvex airfoil. The low-sweep wing helps to reduce spanwise gradients to alleviate the crossflow transition. The sharp leading edges can delay the pressure peak on the airfoil. Favorable streamwise pressure gradients can be obtained as a result, leading to the stabilization of the laminar boundary layer [72]. The supersonic flow compressibility contributes to the stabilization of extensive laminar flow up to a Ma 2.0 [73].

The biggest advantage of the laminar flow wing is to reduce supersonic skin friction drag. The challenge is that the highly constrained laminar flow concept leaves little space for low-boom design.

There is supersonic laminar flow control (SFLC) technology to help achieve extensive laminar flow. However, the difficulty with the SFLC is the complexity of the structural layout resulting in weight penalty.

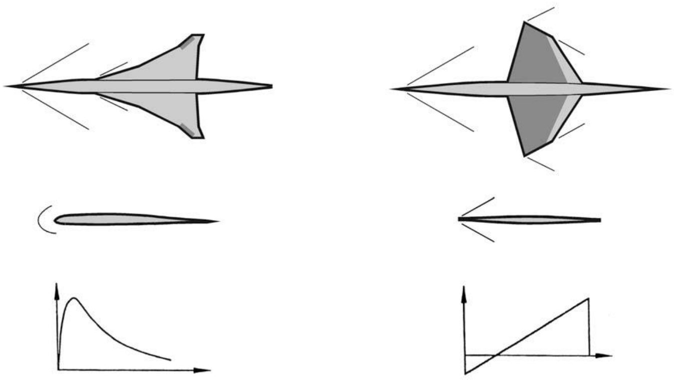


Fig. 32. Comparison of laminar flow on delta wing and the low-sweep laminar design (Source: [69])

6.1.1.4 Oblique wing:

The oblique wing configuration seems to be a promising concept in terms of aerodynamics and sonic boom at lower supersonic cruise speeds.

The oblique wing arrangement is twice the wing length as a symmetrically-swept wing of the same span, sweep and volume, which offers a reduction in volume wave drag by a factor of 16, as depicted in Fig. 33. The lift induced wave drag of the oblique wing is only 1/4th that of the conventional swept wing of the same span and sweep.

The oblique wing mitigates the sonic boom because the lift distribution is more uniform along the vehicle length. Wind tunnel tests have been carried out to determine the magnitude of the ground track sonic boom overpressure generated by an oblique-wing aeroplane cruising at Mach 1.4 at 13,800m. The results show that the oblique-wing configuration produces less sonic boom overpressure at cruise condition than an equivalent swept-wing vehicle [74].

The straight carry-through structure of the oblique wing avoids torques that usually reacted by fuselage structure and makes the structure simpler. One of the primary concerns is the nonlinear aerodynamic behaviour of the asymmetric geometry, which offers challenges in control system design.

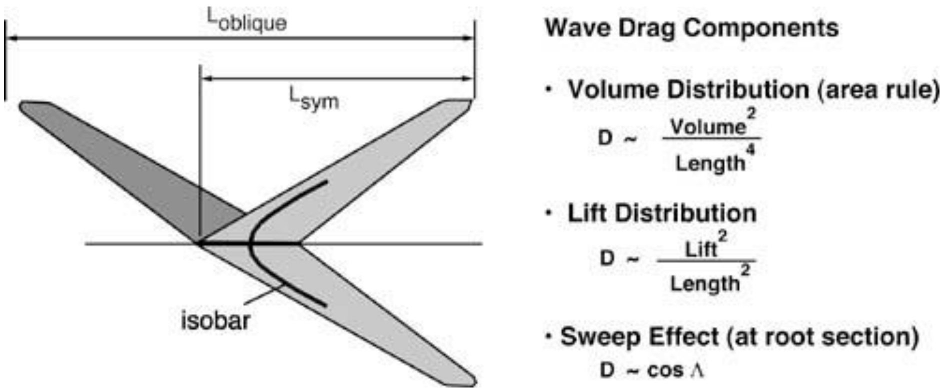


Fig. 33. Oblique wing drag reduction features (Source: [69])

6.1.1.5 Busemann biplane:

The supersonic biplane concept is proposed by Adolf Busemann, therefore, it is called Busemann Biplane. The biplane is believed to solve the two major challenges for supersonic cruise—the supersonic drag and sonic boom problem [75].

Fundamentally, the wave drag is separated into wave drag due to lift and wave drag due to thickness (volume). Even if drag due to lift is inevitable, it can be alleviated significantly by applying the biplane configuration. The configuration is believed to decrease lift induced drag by re-distributing the total lift among the airfoil elements, resulting in a lift reduction on each element and thus reduction in drag, which is called the ‘wave-reduction effect’. Likewise, by choosing the geometries and relative locations of the multi-airfoil, the waves mutually cancel each other to eliminate the wave drag due to thickness, which is called the ‘wave-cancellation effect’ [76]. The biplane can mitigate the sonic boom by the ‘wave reflection effect’. The elements can be configured to reflect the shock wave produced by the upper plane skyward [77]. These effects can be applied to design an ideal quiet and efficient supersonic aeroplane, as depicted in Fig. 34.

The problems with the Busemann biplane occur at the off-design conditions. The choke-flow phenomenon would increase the drag significantly. Even worse, there would be a risky flow-hysteresis phenomenon. Flow control measures, such as leading and trailing edge flaps, can help to alleviate these problems [78]. Previous study on Busemann biplane focus on the aerodynamic aspect. There is few study on the structure. The surface area may increase as the separated surfaces. However, the jointed wing structure can be more efficient. It is hard to judge the mass change without in-depth study.

Fig. 34. Conceptual drawing of a biplane supersonic aeroplane (Source: [78])

6.1.2 Fuselage

The fuselage design is highly constrained considering sonic boom mitigation and wave drag minimization. The basic theories for fuselage design are the supersonic area rule theory and Whitham's theory (see Section 6.2.1) to minimize wave drag and sonic boom intensity respectively.

Wave drag will be effectively reduced by improving the vehicle fineness ratio. Modifying the shape of the configuration to that of the Sear Haack body and smoothing the surface curvature will make a further contribution to wave drag reduction [51]. According to the Seebass-George-Darden (SGD) theory, modifications to the fuselage can contribute to the mitigation of sonic boom intensity [79].

The fuselage volume allocation is represented in Fig. 35. The internal items are arranged inside to achieve an area-ruled fuselage. The main cabin and the fuselage fuel tank locations are the two main variables that have the most influence on the distribution [49]. An SSBJ cabin is designed to typically accommodate 8- 12 passengers, as presented in Fig. 36. Under the category of comfort, the longer the flight time, the wider the cabin should be. The relatively short travel time in an SSBJ should reduce the need for a larger cabin. Configuration studies performed in Ref. [3] indicate that it will be difficult to integrate a large-diameter cabin into a 100,000 lb (45,359 kg) SSBJ. A cross section comparison of G550 subsonic business jet with two supersonic business jet designs is shown in Fig. 37. Integration of large cabin diameters into a minimum boom fuselage, as determined by Seabass-George theory, will be challenging. A possible way is to change the circular cross section to an ellipse or double bubble for more cabin height.

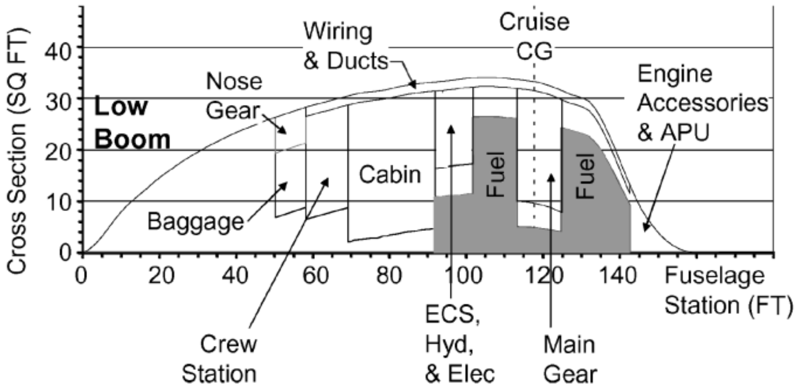


Fig. 35. Fuselage volume packaging (Source: [49])

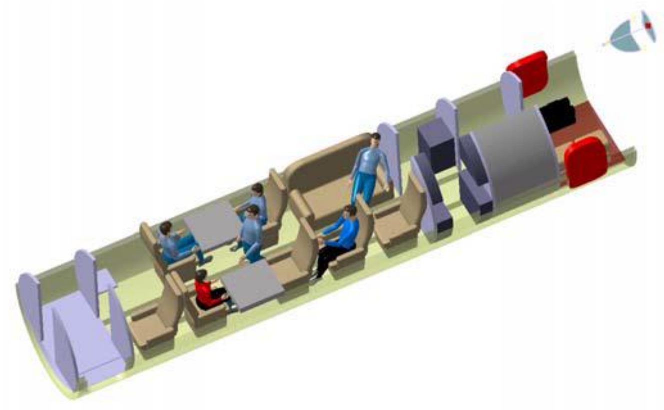


Fig. 36. Typical SSBJ cabin layout (Source: [48])

	G550	TOGW > 150K lb	TOGW = 100K lb
Max Fuselage Diameter	94.0	93.0	80.9
Aisle Height w/ Flat Floor	74.0	75.9	66.0
Aisle Height w/ Notch	n/a	n/a	68.9
Aisle Width above 25 in	20.0	20.0	20.0
Aisle Width below 25 in	20.0	20.0	15.0
Seat Width	26.0	26.0	24.0

(all dimensions in inches)

Fig. 37. Comparison of fuselage cross section (Source: [3])

6.2 Sonic boom

The sonic boom is the biggest obstacle to supersonic aircraft re-entering service. There have been numerous studies on sonic boom regarding the basic theory, prediction methods, flight tests and experiments, and low-boom technologies. The study of the sonic boom phenomenon started with the faster than Mach 1 flight of the X-1 in 1947. Research in the 1950s attempted to understand the properties of sonic boom. Tests significantly increased during the 1960s, with the development of British-French Concorde, as well as the SST programs of the US and the Soviet Union. The space shuttle launch and entry boom minimization were the focus of NASA research during the 1970s to the mid-1980s. The late

1980s saw the early optimism towards large SSTs. Further research worked on human factors issues, sonic boom effects on animals and structures, and sonic boom propagation modelling. Recent research focuses more on supporting the development of SSBJs as large SSTs now seem further into the future [80].

6.2.1 Boom theories

Usually, three distinct regions (as illustrated in Fig. 38) are classified in analysing sonic boom: 1) the near-field region where the flow is fully three-dimensional, 2) the mid-field region where nonlinear distortion of the pressure signature occurs due to atmospheric turbulence, and 3) the far-field region where the pressure signature of the aircraft has acquired a shape that persists to infinity. The N-wave signature features its maximum overpressure (Δp), rise time (τ) and duration (Δt).

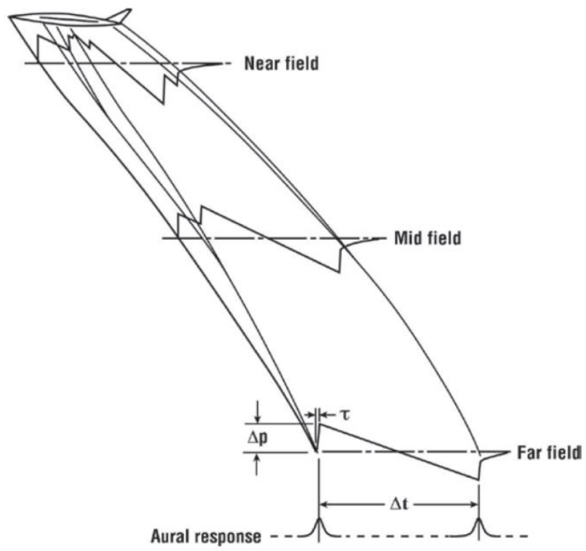


Fig. 38. Sonic boom generation, propagation and evolution (Source: [65])

The Whitham theory [81] is based on the linear theory which provides the correct first order values along a characteristic. By developing a procedure to correct the characteristic location from the zeroth order to the first order, Whitham obtained a uniform first order solution. The theory is known as the ‘F-function' in the following form.

$$F(x) = \frac{1}{2\pi}\int_0^x \frac{A_e''(\bar{x})}{\sqrt{x-\bar{x}}} d\bar{x} \tag{3}$$

For a non-axisymmetric geometry, the effective area A_e combines the effects of both volume and lift.

$$A_e(x,\theta) = A_v(x,\theta) + \frac{\beta}{2q_\infty}\int_0^x L(x,\theta)dx \tag{4}$$

The near-field over pressure δp caused by the aeroplane is directly related to the F-function, as presented in a simpler general form.

$$\frac{\delta p}{p} = \frac{F(\tau)}{\sqrt{B}} \tag{5}$$

Walkden [82] extended the theory by applying the supersonic Area Rule Theory to the sonic boom of wing-body combinations. George [83] initiated a higher order analysis to modify complex configurations to minimize sonic boom, which also played an important role in the subsequently advanced source methods.

The early propagation theories were developed through a uniform atmosphere by the method of geometrical acoustics. The atmospheric turbulence was found to be the main factor that would affect the boom amplitude and shock rise times. Crow [84] successfully developed distortion analysis to his scattering formulation. Rise times were analysed by two successful theories. One is the Burgers equation [85] introduced by Plotkin and George to relate dissipation to turbulence. The other is the theory developed by Pierce [86] to take wavefront folding into consideration.

Sonic boom minimization emerged with the development of sonic boom theories. A major conceptual progress occurred when McLean [87] found that N-wave booms were not inevitable. When taking real atmosphere effects into consideration, the boom on the ground may be mid-field instead of far-field, which made it possible to shape the sonic boom. George [88] pointed out that shocks could be alleviated with a long nose to raise the pressure gently, much like an isentropic spike inlet. George and Seebass [89] developed a theory to minimize shocks by modifying the distributions of both lift and area.

6.2.2 Prediction methods

Theoretically, there are three steps in predicting the sonic boom signatures [90]. The first step is to specify the near-field static pressure signatures around the aircraft. The second step is to propagate the pressure signatures to the ground considering the nonlinear turbulence of the atmosphere. The third step is to calculate the interactions of the boom signatures with the ground. The third step, however, is not usually mentioned in the literature. The roadmap of sonic boom prediction is illustrated in Fig. 39.

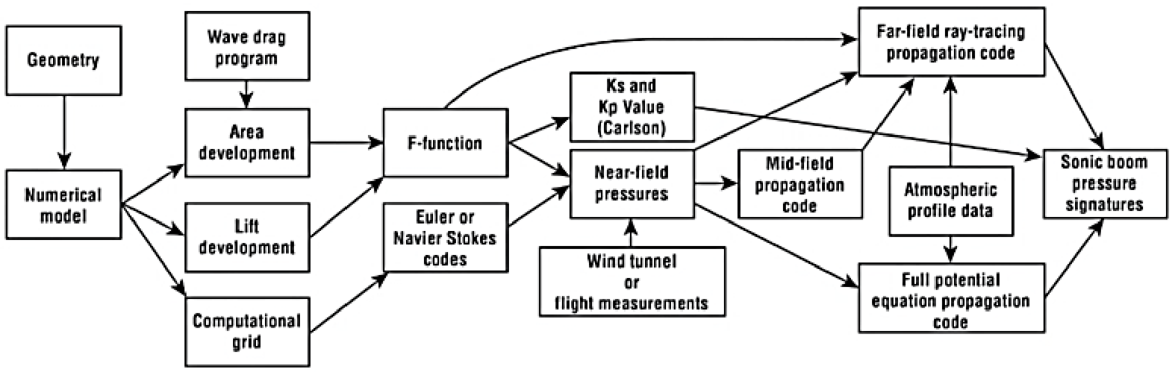


Fig. 39. Ingredients of sonic boom prediction programs (Source: [65])

The path for the F-function approach starts with the parametric geometry model of the aeroplane. Area development for the desired Mach number and azimuth angle is obtained for the geometry model. Lift development is provided from the aerodynamic analysis. The resulting equivalent area distributions are input to the Whitham F-function to get the near-field signature, which then evolves into the ray-tracing code or a mid-field propagation program which better accounts for nonlinear or three-dimensional effects. The output of the latter program is then input to the propagation codes considering the atmospheric distortion to provide the detailed sonic boom signatures at ground level. A third path is indicated where the K_s, K_p, and K_t factors are obtained using the Carlson methodology [91].

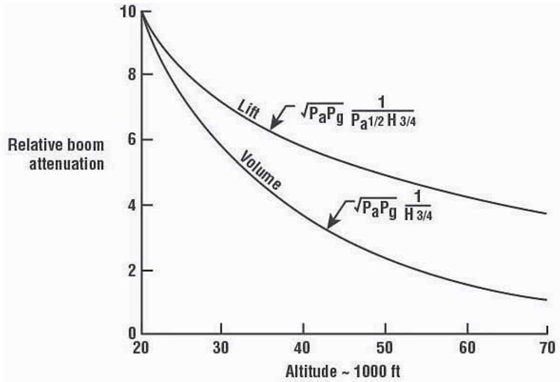
The CFD approach starts with a computational grid. Ideally, the code should have an adaptive grid capability to concentrate the grid in the vicinity of shocks, or a shock fitting routine, since shock jumps tend to smear as the distance from the configuration increases. In most cases, Euler equation codes are used since, for vehicles at cruise conditions, viscous effects are second order [65]. Boom predictions with Euler equation have been used by various researchers [92-94].

The wind-tunnel approach was developed so as to use the near-field pressures measured on small scale supersonic aeroplane models. These models provide the same input as the primary path. This alternate path is of great use when sonic boom prediction is required for non-standard configurations, for vehicles operating at extreme conditions, and particularly at relatively high Mach numbers. In these special cases, the results of experimentally based methods are more representative than numerical predictions.

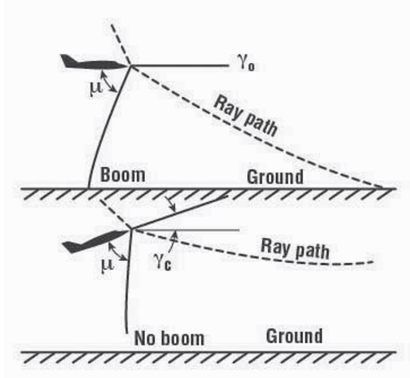
6.2.3 Low boom solutions

6.2.3.1 Mitigation through aircraft operations

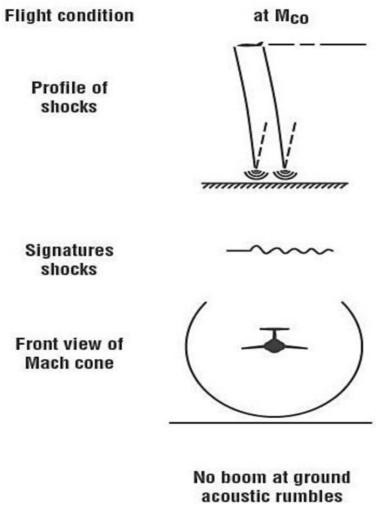
Several approaches to sonic boom minimization through the use of flight operations are summarized in Ref. [65]: (1) increase the flight altitude to decrease the impact of volume and lift on the boom, as illustrated in Fig. 40(a), and (2) use a climbing flight path to delay the arrival of the boom to the ground, as illustrated in Fig. 40(b), and (3) operating at a speed below the cutoff Mach number without the boom reaching the ground, as illustrated in Fig. 40(c), and (4) tailoring the flight path over heavily populated areas, the schematic is illustrated in Fig. 40(d).



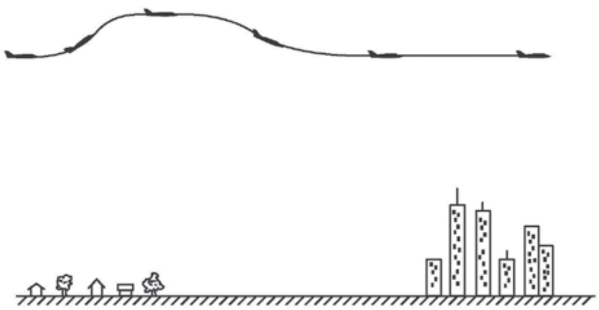
(a) Sonic boom attenuation with altitude



(b) Schematic of shock-ray pattern



(c) Boomless flight at Mach cutoff



(d) Schematic of pull-up manoeuvre

Fig. 40. Aircraft operations for sonic boom mitigation (Source: [65])

6.2.3.2 Mitigation through aircraft shaping

Sonic boom signature mitigation through aircraft shaping is based on the equivalent area concept established by Whitham [81] and Walkden [82]. To reduce the overpressure for a given design, the equivalent area must be spread so as to increase the slenderness ratio as illustrated by the three sketches shown in Fig. 41. The sonic boom intensity is inverse proportion to the slenderness ratio ($\Delta p_{max} \propto d/L$). Thus the larger the L/d, the lower the maximum overpressure will be.

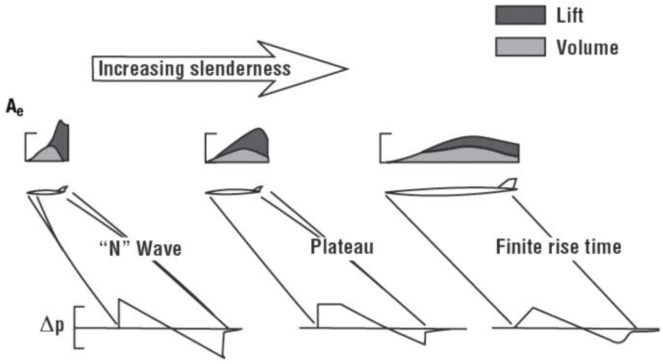


Fig. 41. Relationship of signature shapes to vehicle area development (Source: [65])

Direct shape optimization [95] is a widespread method to optimise low-boom configurations. The inverse design approach is the focus of present research [96]. The inverse design approach based on the Seebass-George-Darden (SGD) boom minimization theory is proposed to design the fuselage-wing configuration [97]. As the schematic in Fig. 42 indicates, the inverse design process begins with the calculation of the effective area (A_e) for a given configuration. A_e is fed back to Whitham's F-function method to generate the boom signature. The configuration's low-boom target signature is approximated by modifying the curve of the wing/body cross section area distribution [6].

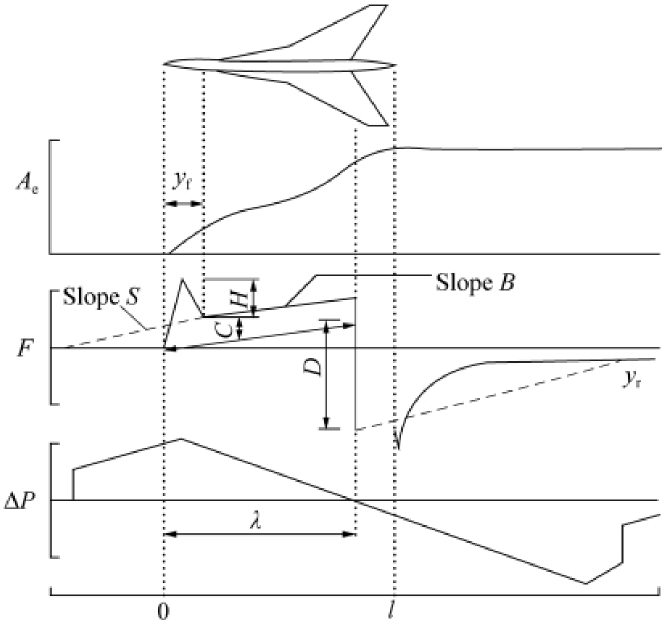


Fig. 42. Schematic of SGD method (Source: [98])

Lift distributions can be used to control the strength and location of shocks by means of planform changes, wing section thickness, wing twist, wing camber and dihedral. Active lift control is a way to mitigate sonic boom by modifying the longitudinal lift distribution with no effects on the trim state [99]. SAI hold a patent to control the thickness and camber by deploying a device to generate expansions ahead of compressions in off-design conditions. This technology enables to achieve low intensity sonic booms [100].

6.2.3.3 Mitigation through exotic concepts

The method of 'phantom bodies' has found application to test the sonic boom level. Different magnitudes of heating flows are supplied to the incoming flow in the numerical research. A 20% sonic boom level reduction was observed in the study [101].

Miles et al. [102] propose an approach of energy addition to mitigate the sonic boom. In this approach, an energy addition process contributes to increase the apparent length of the aircraft and thus to reduce the extent of shock-wave coalescence. Here, an initial rise of 0.8 psf reduced to 0.2 psf with a peak rise of 0.6 psf.

The extendable nose spike is a mass addition developed to alter the shock wave field. The Quiet Spike concept [103] patented by Gulfstream Aerospace has achieved a 0.25 psf initial shock compared 0.4 psf without spike and an increase of 25% in rise time [93]. There are some other exotic concepts that can be found in Ref. [65]. Not only for these exotic concepts, even for other sonic boom mitigation measures, there will always be cost, such as loss in performance, mass penalty or energy increase.

6.2.4 Flight tests and experiments

Wind tunnel and flight tests help to support the sonic boom prediction methods by measuring the near-, mid- and far-field shock flow fields. Low-boom solutions were tested during many flight test programs. The early flight tests focused on gaining insight into the nature of the wave flow field, measuring the near-field shocks, and insight into effects of aircraft lift.

NASA carried out tests on the SR-71 to validate CFD codes by measuring the near- and mid-field pressure signatures on a probing aircraft [104]. A reasonable agreement was shown in the comparison of flight-test data and the computed pressure signatures [105]. During DARPA's Shaped Sonic Boom Demonstrator (SSBD) program [106], an F-5E aircraft was modified, particularly in the forebody region, to produce a flat-top sonic boom signature, as shown in Fig. 43. The program successfully demonstrated the sonic boom signature can be modified through aircraft shaping, as indicated in Fig. 44. A total of 56 in-flight signatures on the F-5E and 68 on the SSBD were generated suitable for methodology and tool validation. A high correlation is seen between the measured and predicted signatures proving the accuracy of the CFD tool [107].

Fig. 43 Modified F-5E aircraft for SSBD program (Source: [65])

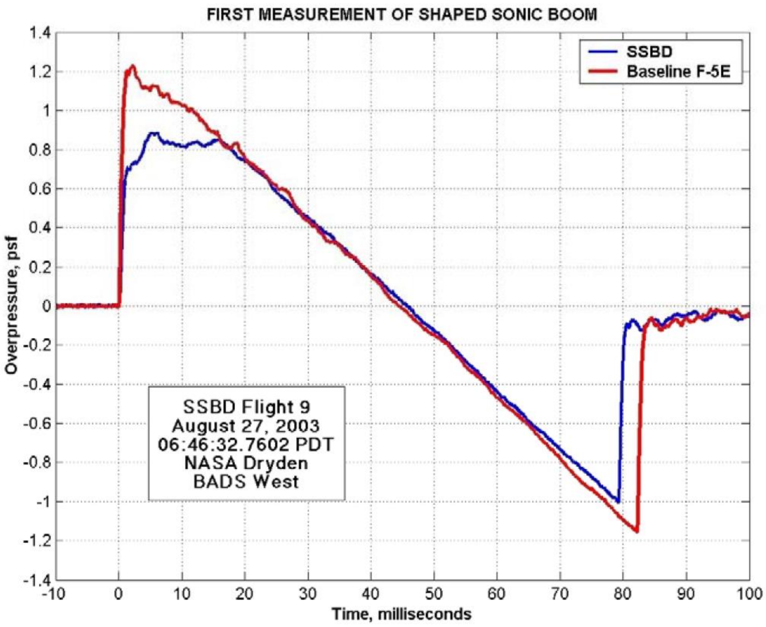


Fig. 44 Baseline and low boom signature comparison (Source: [106])

Gulfstream and NASA cooperated in the flight trails which aimed to test the effect of the Quiet Spike in sonic boom mitigation. The Quiet Spike was adapted to an F-15B flight research aircraft and a total of 32 research flights were conducted. The schematic of the Quiet Spike, as shown in Fig. 45, is that the series of weak shocks generated by each of the telescoping sections will not coalesce into an N-wave but propagate to the ground in parallel fashion. The Quiet Spike has proven that it can play a significant role in achieving the desired area distribution for a low-boom aeroplane [108-110].

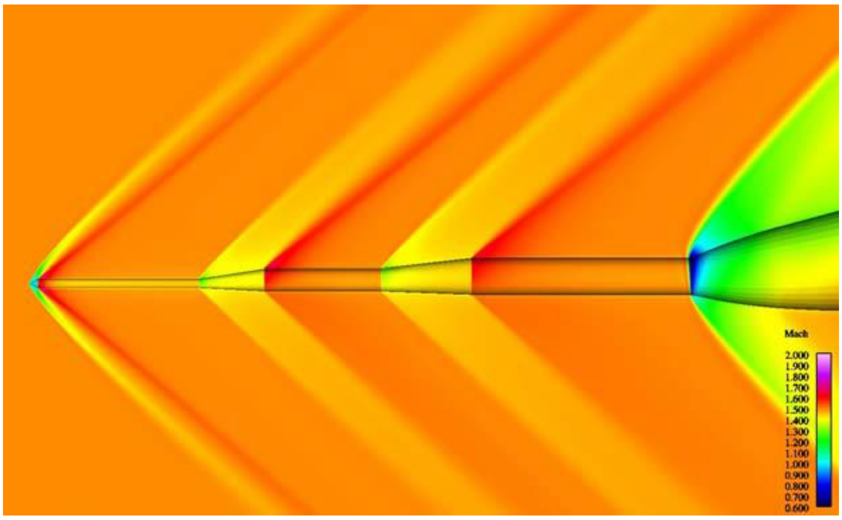


Fig. 45 CFD analysis of Quiet Spike structure (Source: [108])

The D-SEND (Drop test for Simplified Evaluation of Non-symmetrically Distributed sonic boom) project was commenced by Japan Aerospace Exploration Agency (JAXA) for the demonstration of the low boom design technologies. The project is conducted in two phases, the D-SEND#1 and the D-SEND#2. The D-SEND#1 drop tests were carried out twice from a balloon. The low-boom model signatures compared with N-wave model signatures plotted in Fig. 46 indicate the success of the project. The D-SEND#2 was to drop an unmanned aeroplane (Silent Supersonic Technology Demonstration, Fig. 47) at an altitude of up to 30 km to validate the shock waves reduction.

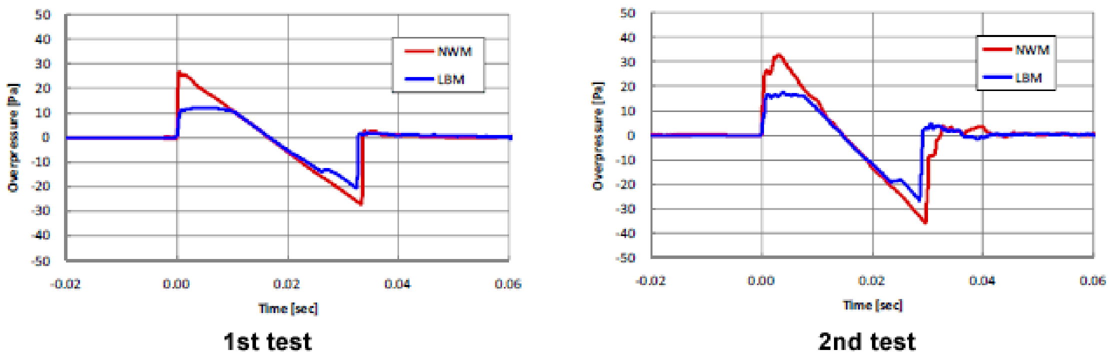


Fig. 46 Measurement results of D-SEND#1 (Source: [111])

Fig. 47 D-SEND#2 Silent Supersonic Technology Demonstration (Source: [112])

During the NASA N+2 Advanced Supersonic Commercial Transport Aircraft project, tests were carried out in NASA Ames 9’×7’ supersonic wind tunnel to validate boom shaping tools. The results saw sonic boom reductions in both front and aft near-field which matched predictions [113, 114].

6.3 Aerodynamics

Another central challenge for SSBJ design is to minimize supersonic drag under the stringent civil aviation regulations and mission requirements. The dilemma of balancing the supersonic cruise and subsonic performance is sketched in Fig. 48. The highly swept wing will provide a higher supersonic lift to drag ratio at supersonic speeds to help meet the long range requirement. However, its lower aerodynamic efficiency at subsonic speeds results in more fuel consumption.

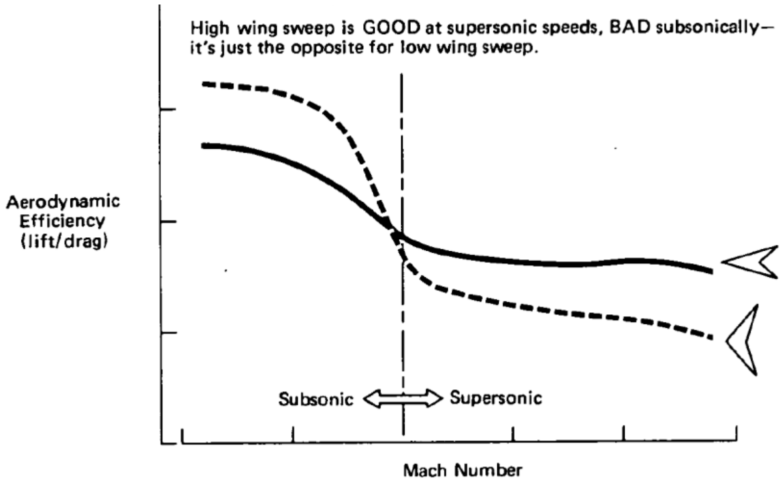


Fig. 48. Supersonic cruise aircraft aerodynamic dilemma (Source: [115])

6.3.1 Aerodynamic efficiency

The level of aerodynamic efficiency (L/D) at subsonic and supersonic flight are both important. From the analysis in Section 5.1, a small increment of L/D in supersonic cruise would result in a significant improvement in range. It is estimated that if the Concorde's L/D drop to 7 in subsonic regime, 40% of the fuel would be used in the low-speed flight. The supersonic cruise efficiency is directly and indirectly related to most of the challenges.

Promising means to improve the aerodynamic efficiency are referred to in Ref. [115]. The variable sweep configuration seems to be an obvious way to cope with subsonic and supersonic speed regimes. Though military aircraft have adapted this concept, difficulties do exist to apply it to a highly constrained commercial transport. The swept-delta or delta-ogee wing, used by Concorde and American SST, is still a compromise between subsonic and supersonic L/Ds. Leading- and trailing-edge flaps have been verified to be able to improve the aerodynamic performance of a supersonic configuration at low speed [116, 117]. There are novel ideas to solve this dilemma, such as the supersonic bi-directional flying wing concept [118].

6.3.2 Supersonic drag

Supersonic drag consists of several components. A good drag breakdown is provided in Ref. [119]. Basically, supersonic drag is categorised into friction drag, wave drag, and other drag (vortex, interference, etc.). The wave drag produced by the cross-sectional area distribution is called ‘wave drag due to volume’, while the wave drag produced by lift generation is named ‘wave drag due to lift’. These supersonic drag components are summarized in the following equation:

$$C_D = C_{Df} + C_{Dwv} + K(C_L - C_{L0})^2 + \Delta C_{Di} \tag{6}$$

where C_{Df}=friction drag, C_{Dwv}=wave drag due to volume, $K(C_L - C_{L0})^2$=wave drag due to lift, ΔC_{Di}=other drag. Therefore, based on supersonic linear theory, the supersonic drag can be reduced in different aspects. The effects of drag reduction methods used in JAXA’s experimental aeroplane are depicted in Fig. 49.

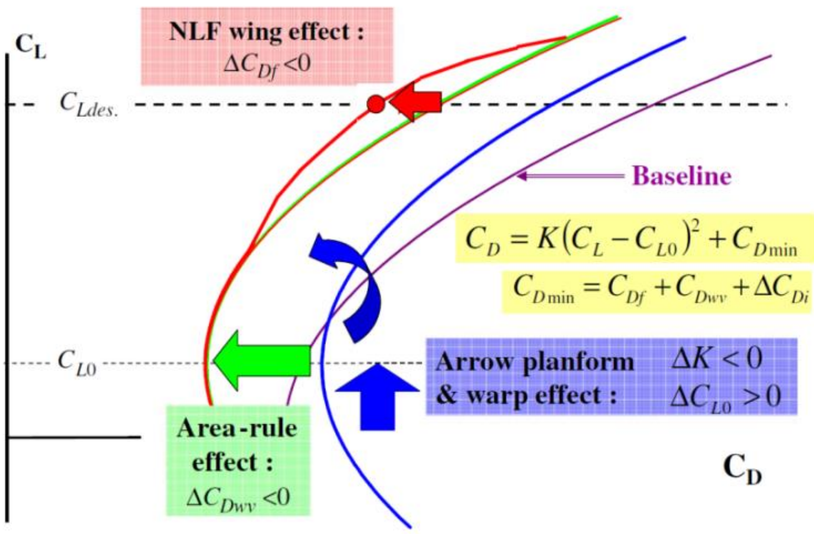


Fig. 49. Effect of each drag reduction concept (Source: [119])

Wave drag starts to contribute to the total drag in the transonic regime, while it becomes significant for supersonic cruise aeroplane, which is a major barrier for an economically viable SSBJ. An indepth review on two nonreacting wave drag reduction approaches, shock weakening by altering the shock formation processes and favorable wave interferance, can be found in Ref. [120]. Possible technologies to resolve the challenge are introduced in Ref. [2]. Modifying the flow field, including active flow control, virtual shaping, and energy addition [121] can reduce supersonic wave drag. Unconventional designs, such as an oblique wing, present a fundamentally different solution to the problem. However, it will take a long time to verify these approaches because of the low maturity levels. High fidelity analysis is expected to be needed to explore the feasibility of novel technologies. This technology should be introduced via a multidisciplinary design analysis and optimisation environment, taking other design requirements into consideration.

6.3.3 Supersonic laminar flow

Laminar flow design is a key technology that could have a large aerodynamic performance benefit for the SSBJ. A quantitative drag breakdown of the conventional supersonic aeroplane is shown in Fig. 50. It is not difficult to see that skin friction drag represents a significant contribution to total drag which justifies efforts to reduce it.

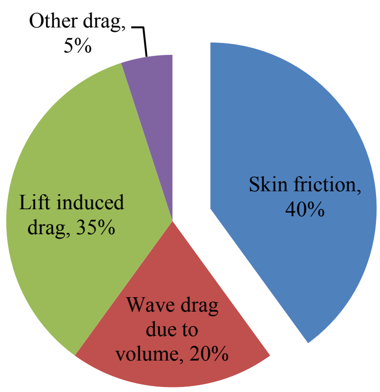


Fig. 50. Supersonic drag components (Source: [122])

As shown in Fig. 51, an increase in laminar flow fraction from 5% to 70% is needed to extend the range of a typical SSBJ from trans-Atlantic to trans-Pacific. Fig. 52 depicts the weight saving for a 5000 nm jet. Increasing the laminar flow fraction from 10% to 60% can drop the take-off weight by a half [123].

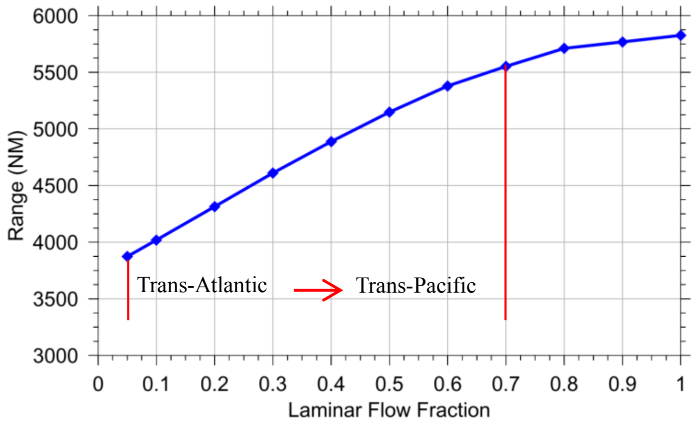


Fig. 51. Impact of laminar flow on range (Source: [123])

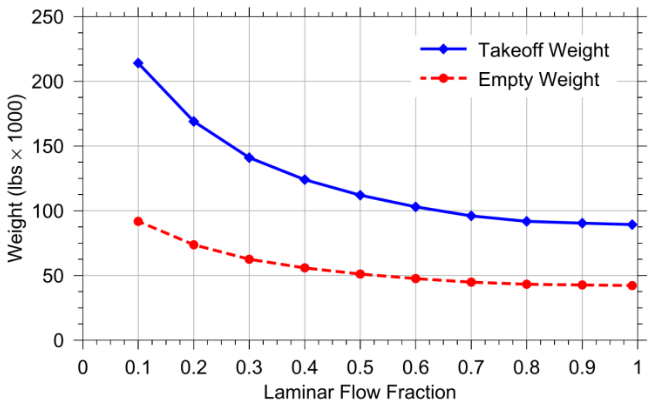


Fig. 52. Impact of laminar flow on weight (Source: [123])

Natural laminar flow (NLF) is a passive way to achieve extensive laminar flow by design the wing shape carefully. A NASA F-104 sublimation test in 1959 illustrated the extent of stable natural laminar flow. Laminar flow over 50% of wing chord was achieved at an approximate three-quarters span location [124]. NASA flight test on F-15B demonstrated an impressive amount of laminar flow, Fig. 53.

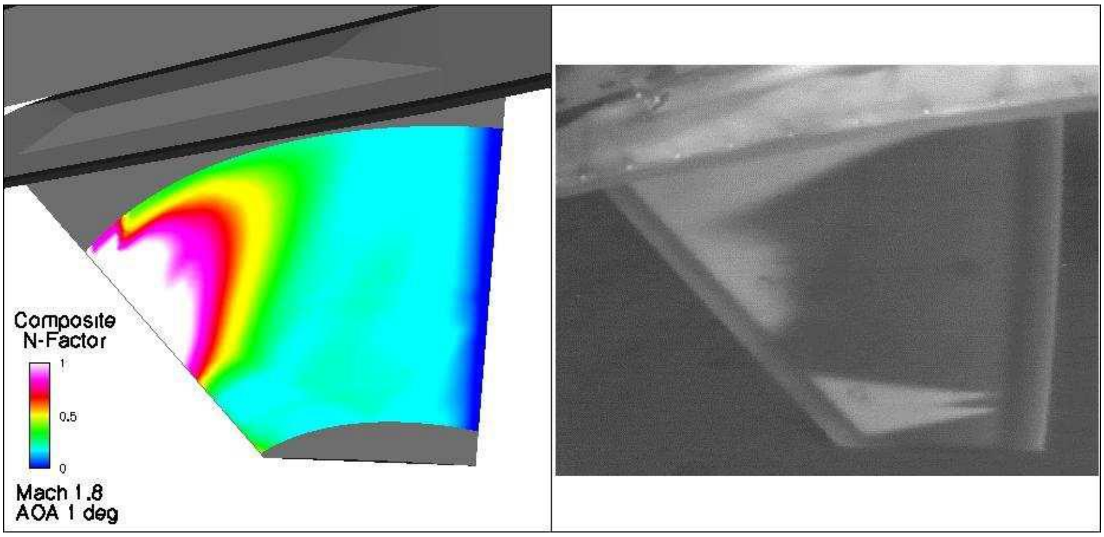


Fig. 53. F-15 full-chord laminar flow simulation and flight test (Source: [72])

The National Experimental Supersonic Transport (NEXST) project was performed by JAXA to validate the natural laminar flow wing design developed by CFD technology. The flight testing was carried out on a 1/10 scale cranked arrow wing aeroplane, as shown in Fig. 54. The laminar flow was verified to cover an area of over 30% of the wing upper surface at Mach 2.0 [45].

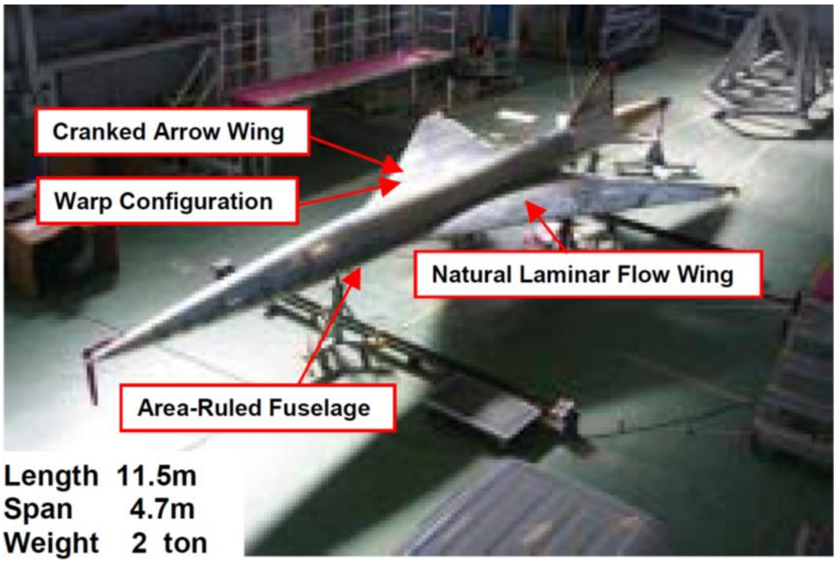


Fig. 54. NEXST project aircraft (Source: [125])

Supersonic Laminar Flow Control (SLFC) is applied to actively keep the boundary-layer flow from transitioning to turbulent flow at supersonic speeds. SLFC schemes include slot suction, porous suction, wall cooling [126, 127], and distributed roughness [128, 129]. NASA has successfully achieved an extent of 46% supersonic laminar flow on a crank arrow wing configuration (70° inboard and 50° outboard). Active control technology uses a perforated titanium glove [130], as shown in Fig. 55. However, this technology is not mature enough to go from laboratory to daily operation.

Fig. 55. F-16XL flight test with LFC glove on the left wing (Source: [131])

6.4 Propulsion system

As with all aspects of supersonic aircraft design, the propulsion system is heavily constrained by numerous requirements. Better fuel efficiency is, of course, of high importance to improve the payload fraction and will contribute to a reduction of emissions. Novel fuel propulsion systems provide another way of solving these problems. Fuel system and aircraft sizing need to be designed carefully due to high fuel fraction.

6.4.1 Engine selection

The engine selection for an SSBJ is not easy considering the three-speed regimes (subsonic, transonic and supersonic) that the aircraft will be operating in. The dilemma is that propulsion systems that perform optimally at supersonic speeds do not perform very well at subsonic speeds, and vice versa. Trade-offs need to be evaluated between the engine efficiency and the stringent environmental requirements. In fact, the winner will be chosen because of its balanced behaviour over the whole flight spectrum.

Rolls-Royce studied different engine concepts for second generation quiet supersonic transports. The Variable Cycle Engine (VCE) was selected after a comparison with the Variable Cycle Conventional Turbofan (CTF), Mixed Nozzle Ejector (MNE) and Mid-Tandem Fan (MTF) configurations. Inlet and nozzle requirements to solve acoustic problems appropriate to VCE were also considered [132].

NASA compared six candidate engine concepts for the HSCT project. These propulsion systems include the turbojet, turbine bypass engine, mixed flow turbofan, variable cycle engine, FLADE (Fan-on-blade) engine and the inverting flow valve engine. The mixed flow turbofan (Fig. 56) is preferred for its good performance, low weight and low risk and complexity. Low-noise features helped the FLADE engine to be the second choice. While the VCE was crossed off the list because of its heavier weight caused by the additional secondary outer bypass duct to the mixed flow turbofan [133].

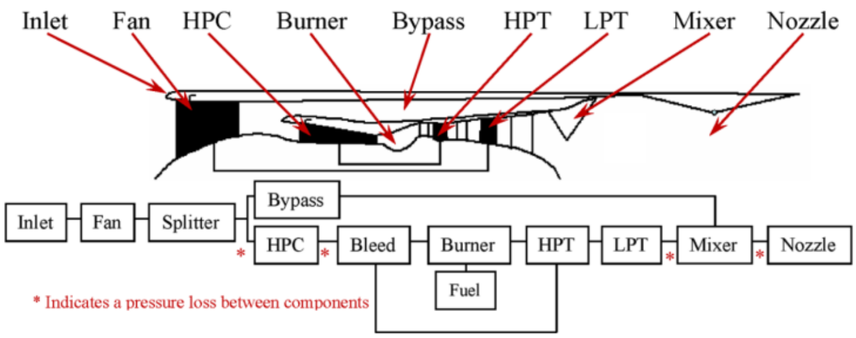


Fig. 56. Mixed flow turbofan schematic and model (Source: [134])

A conceptual design of an SSBJ propulsion system was performed under NASA's Ultra-Efficient Engine Technology Program (UEETP). The program developed several key technologies (highly loaded turbomachinery, emissions reduction, materials and structures, controls and propulsion-airframe integration) to enhance the performance of future supersonic transports. The high-level goals of the program are a 70% reduction in take-off and landing NOx and an 8% decrease in mission CO_2 emission. The study concluded in the design of a mixed flow turbofan engine with a fan pressure ratio of 0.3 and a throttle ratio of 1.143 [135].

The overall propulsion system design is significantly influenced by the engine cycle selection, which is particularly true for supersonic cruise aeroplanes. Gulfstream Aerospace has conducted research to compare the integrated performance of two Rolls-Royce turbofan-derived propulsion systems, an advanced highly variable cycle (HVC) engine and a more conventional high bypass cycle (HBR) engine. The assessment was performed on Gulfstream's low-boom SSBJ concept, as shown in Fig. 11. The results indicated that the HVC, compared to HBR, is 8% superior in terms of elapsed integrated fuel burn improvements and up to 11% increase in time-to-climb advantages [136].

On-design engine performance is determined by design choices. This helps to examine the engine performance trends with design variable changing and to narrow the range for each design parameter. Off-design conditions are also important to determine a selected engine performs at all operating conditions in its flight envelope [137]. Off-design analysis of supersonic aircraft engines can be found in Ref. [134].

6.4.2 Novel fuel

Liquid hydrogen (LH_2) is a promising alternative energy source compared to kerosene considering weight minimization, sonic boom mitigation, and emissions reduction.

A conceptual design study evaluated the feasibility of the hydrogen-fuelled SST and made a comparison between LH_2 and kerosene in terms of weight and sonic boom. By using LH_2, the weight reduces by around 30% and a 13PLdB reduction in sonic boom noise can be seen [138].

In another study, the SST fuelled by LH_2 is calculated to reduce sonic boom about 2.2-4.3 PLdB, while a 1.3EPNdB higher airport noise will result due to the higher jet velocity. However, the climate change impact becomes more severe because the water vapour emitted to the stratosphere is 2.6 times higher [139].

6.4.3 Emission and noise

The Central Institute of Aviation Motors (CIAM) optimized an SSBJ NO_x emission model to study the effects of the emission parameters under a set of criteria. The results concluded that a 15-18% NO_x emission reduction can be reached with range and jet noise criteria and the range would reduce 8-10% as a penalty. Optimization of the design variables allows an NO_x reduction of 25-30% under three criteria (range, noise and emission) with range losses by merely 2-3% [140].

The five-year ESPR project summarises the achievements of environmentally compatible technologies for the next generation SST. The jet noise can be reduced 3.1 dB by utilising a mixer-ejector (Fig. 57) and the fan noise reduction of 3 dB was achieved by the concept of swept/leaned stator vanes in the bypass duct. The NO_x emission level goal of 5 g/kg E.I. can be realized by benefiting from an LPP (Lean Premixed Prevaporized) combustor, NO_x feedback AI control and CMC liner walls. The third target of a 25% CO_2 reduction from the 1999 technology level was achieved through the engine weight reduction and cooling airflow [141].

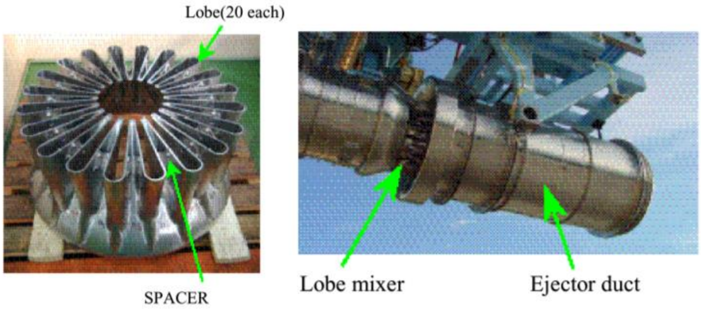


Fig. 57. Mixer-ejector configuration (Source: [141])

6.4.4 Fuel system

A characteristic of the SSBJ is its high fuel fraction, which causes challenges on the fuel packaging and fuel system management. The fuel tanks are distributed throughout the wing and fuselage, Fig. 58. Fuel need to be pumped from tank-to-tank to actively manage the aeroplane centre of gravity to improve performance and mitigate sonic boom.

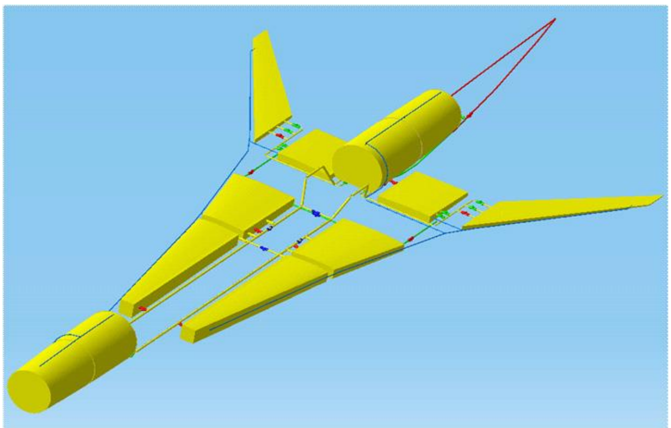


Fig. 58. SSBJ fuel system layout (Source: [48])

6.5 Structure

Designing an aircraft for supersonic flight results in many additional structural issues that should be taken into consideration in the design phase, such as thermal effects, supersonic panel flutter and acoustic fatigue. The high fuel fraction requirement for the SSBJ concept to achieve the desired range demands a minimum structural mass. Therefore, there is an increasing need for optimal structure design and materials selection.

6.5.1 Structural design

As shown in Table 5, the aerodynamic heating effects become severe as the Mach number increases. There will be a significant thermal protection problem over Mach 2.0. Thermal protection measures result in a weight penalty, which is unacceptable for business class aircraft. A limitation on the Mach number has alleviated the problems induced by aerodynamic heating.

Table 5. Aerodynamic heating effects (Source: [51])

Cruise Mach	Surface Temperature (°C)	
	Peak	Average
1.6	65	40
1.8	85	65
2.0	120	95
2.2	155	125

The SSBJ is usually featured with swept thin wings with long root chords, which is required for wave drag reduction. High speeds increase the lifting surface susceptibility to high-frequency flutter modes. By way of experience that a flexible airframe combined with aft mounted engines tends to be susceptible to flutter [142]. Smart wing structures are mentioned to reduce wing flutter [143]. The supersonic panel flutter analysis will need high-fidelity finite element analysis [144].

The sonic fatigue problem was studied in NASA's HSR program. Honeycomb structures were tested and analysed for its fatigue resistance ability. It is found that the core thickness should be greater than 0.5 inches and the panel length less than 50 inches. The skin-stringer fuselage concept is regarded as the most promising structure to meet the sonic fatigue resistant requirement. Addition damping techniques are to add substructure or enlarge material gages [145].

6.5.2 Materials

It is clear that different parts of a supersonic aeroplane are heated up to different temperatures; hence different parts should be designed with the most appropriate materials. Polymer matrix composites and most aluminium cannot maintain their mechanical properties at 120°C or above (greater than Mach 2.0) for long-term operation [146]. Titanium's high melting point (1668°C) ensures the aerodynamic heat would not have any adverse effects on the aircraft structure. However, it is applied in limited parts as a result of the high density. A review of supersonic aircraft material selection [147] suggests possible materials for aircraft cruise speed up to Mach 2.0. The fuselage can use aluminium 2090-T651, 7075-T6 and 8090-T651 (for nose). Commercial grade CFRP can be applied for the wing, while Ti-6Al-4V or other Ti can be used for the skeleton. NASA's HSR program has found that IM7/PETI-5 is the potential material for high-speed supersonic aircraft. This material can maintain its mechanical capacity at 350°F (177°C) and its capability to resist fatigue damage is extremely high [145].

An appropriate Material Selection Chart is usually referred to for supersonic aircraft material selection [147]. Progress has been made in developing an efficiently computer-aided material selection system for the design of advanced supersonic aircraft [148].

6.6 Design methodologies

6.6.1 Sonic boom prediction codes

Normally, the sonic boom prediction consists of two parts: near-field pressure generation and boom propagation. There have been numerous codes for sonic boom prediction. Some of them are sorted in Table 6.

Table 6. Sonic boom prediction codes

Codes	Task	Comments	Feature	Source & Available
HWAVE	Volume Distribution	Obtain Mach slice area	Also used for wave drag	1964, NASA [149]
LSTAR	Aerodynamic Analysis	Estimate wing nonlinear aerodynamic characteristics at supersonic speeds	Nonlinear theory	1980, NASA [150]
USM3D	Aerodynamic Analysis	Finite volume method	Unstructured flow solver for unsteady flows	1990s, NASA [151]
Cart3D	Aerodynamic Analysis	3D Cartesian grid generation and Euler flow solution techniques	CFD method for off-body pressure distribution	1995, NASA [152]
Hayes/ARAP Code	Boom Propagation	Prediction the evolution of an aircraft's pressure signature	Based on the Whitham theory (F-Function)	1969, Aeronautical Research Association of Princeton [153]
Thomas's code	Boom Propagation	3-D flow solver for ground signature prediction	Based on a modified linear theory (not F-Function)	1970, NASA [154, 155]
TRAPS	Boom Propagation	Follows Hayes' formulation; use ray distance as its independent variable;	Add secondary boom capability to the ARAP; Nonlinear theory	1980, NOAA [156]
PBOOM	Boom Analysis	Evaluate sonic boom of actual configuration	AWAVE, ALIFT & ARAP	1983, NASA [157, 158]
JBYMAX	Boom Propagation	Combine the previously separate equivalent area and F function development with a signature propagation method	Linear theory method	1983, George Washington University [157]
ZEPHYRUS	Boom Propagation	Application of molecular relaxation to the sonic boom; Inhomogeneous, windy atmosphere	Mixed time and frequency code	1991, The University of Texas at Austin [159]
MDBOOM	Boom Propagation	Mid-field pressure signature did not decay as fast as the near-field decay of the Thomas code.	Linear code based on the Thomas code	1992, Boeing [160]
PCBOOM3	Boom Prediction	Three major inputs: the aircraft, the atmosphere and the aircraft manoeuvre	Extension of the Thomas code	1996, USAF [161]
BOOM-UA	Boom Analysis	Automate the process of mesh generation, solution adaptation, and signature extraction and propagation.	Numerical method	2004, Stanford University [92, 162]
sBOOM	Boom Propagation	An approach to predict the sonic boom ground signatures accurately by numerically solving	The augmented Burgers equation entirely in the time domain	2011, National Institute of Aerospace [163]

Several practical ways of different fidelity have been concluded as follows [164]: For the low-fidelity sonic boom analysis, A_e due to lift can be generated by LTSTAR [150] and A_e due to volume can be generated by HWAVE [149]. The boom propagates to the ground with ARAP [153] or sBOOM [163]. For the medium-fidelity option, the total A_e comes from the CFD simulation, which is then propagated utilising sBOOM. The highest fidelity option used the mid-field pressure distribution from Cart3D [7] or

USM3D [165, 166] and propagates the signature using either PCBOOM [161] or sBOOM.

6.6.2 Integrated design environment

The primary challenges in the design of a supersonic cruise vehicle are to increase the efficiency and to remove the environmental and performance barriers. Recognizing that these barriers are not captured by traditional disciplinary analysis, the top-level goal of SSBJ design is to build a practical multidisciplinary design and analysis environment, where a global optimization algorithm is inside the framework. There have been many attempts to apply multidisciplinary optimization to SSBJ design throughout the literature, such as ModelCenter, Program for Aircraft Synthesis Studies (PASS) [167], the CAD-based Automatic Panel Analysis System (CAPAS) [46], and the Flight Optimization System (FLOPS) [168].

GENUS is a multidisciplinary aircraft design analysis and optimization environment developing at Cranfield University. GENUS consists of nine modules: 1) geometry, 2) mission, 3) propulsion specifications, 4) mass breakdown, 5) aerodynamics, 6) propulsion, 7) packaging and C.G., 8) performance, and 9) stability and control. Three optimization methods have been implemented into the program, including a gradient based optimizer, a genetic algorithm, and a hybrid algorithm. This aircraft design environment has been successfully used in a hypersonic space design [169] and a blended-wing-body design [170].

6.7 Summary

There are various technologies appropriate to SSBJs' design challenges. In fact, they are of different levels of maturity. Technology Readiness Levels (TRL) are introduced to quantify technology maturity to reduce risk, enhance cost effectiveness and safety. TRL 6 is expected to incorporate new technologies into commercial aviation products. A number of technologies mentioned in this section have been evaluated in

NASA's N+3 Supersonic Program [171]. The enabling technologies to realize environmentally acceptable and economically viable supersonic vehicle are listed in Table 7.

Table 7. TRL roadmap for SSBJ (Source: [171])

Technology	Goal	Description	Benefits	TRL
Swing canard	Efficiency, boom	Deploy canard only at low speeds to control trim and stability	Lower drag, better boom	9
Oblique wing with fuselage	Efficiency, boom	Oblique angle of wing could be adjusted in flight about a single pivot	Better adapts to low speed and high-speed optimum sweep. Less of a weight penalty than a standard swing wing. Reduce boom	6
Variable sweep outboard wing panels	Efficiency, noise, boom	Variable sweep of wing using pivots or other mechanical system	Easier to balance low-speed take-off requirements with high-speed drag and boom goals, less weight than full variable sweep wings	9
Quiet spike	Efficiency, boom	Extending and retracting spike, extends for cruise to increase effective length of aeroplane, retracts for better landing	Reduce boom	5-6
Lift distribution control	Efficiency, noise	Ability to conform portions of configuration/control lift surfaces	Ability to control lift, decreased drag, lower noise	2-3
Configuration shaping	Boom, efficiency	Shape configuration to close fore and aft shock to acceptable levels using advanced MDO techniques	Optimized boom configuration capable of achieving 70 PLdB	1-2
Plasma boom optimization	Boom, efficiency	Use plasma generators to change airflow at key locations on aircraft and dissipate shocks	Reduce boom without having to heavily constrain the configuration	2-3
Distributed roughness laminar flow	Fuel efficiency, range	Distributed bumps on aircraft surfaces. Creates acoustic disturbances out of phase with crossflow disturbances and maintains laminar flow on swept wings	L/D+ 1 to 1.5, increased efficiency at higher Mach, less friction/drag, reduction in weights	3
Low noise/high-performance nozzle	Airport noise, fuel efficiency	Lower the engine noise through various methods without much weight and efficiency penalties	Meet noise and efficiency goal	3
VCE	Airport noise, fuel efficiency, sonic boom	Advanced turbofan engine with adaptive cycle features. Similar to conventional mixed-flow turbofan with secondary outer bypass duct	Smaller, lighter propulsion system that meets airport noise goals	3
Thrust vectoring	Boom, efficiency	Vector engine exhaust slightly downward during cruise to improve boom	Reduce aft shock without having to heavily constrain configuration	6
CFD-based MDAO	Boom	Shapes lifting surfaces to low boom targets	Optimized boom configuration capable of achieving 70 PLdB	2-3
Synthetic cockpit vision	Efficiency	Use TV camera system to give pilot better visibility where nose is in the way	Eliminates need for folding nose or any other design compromises necessary for the pilot to see the runway	2-3
Windowless cabin	Efficiency	Eliminate windows and replace with TV flat-screens	Huge weight savings from eliminating holes in structure, manufacturability benefits, cabin noise benefits	6

7. Conclusion

The small-size SSBJ has been consistently regarded as the pioneer of the next-generation supersonic civil transport. The steady growth in air traffic calls for more efficient, faster commercial transport. Several studies lead to a convincing high-end market in business class transport. Regulations appropriate to supersonic airliners need to be introduced in the near future as the studies on sonic boom acceptance continue. The need to reduce the sonic boom loudness and supersonic cruise drag are of vital importance.

There seems to be a common view on the mission specifications of the SSBJ. With the trans-Atlantic ability, the number of passengers between 8 and 12, and a cruise Mach number of about 1.8, the SSBJs are highly constrained by environmental concerns. However, it is not easy to balance these concerns with the 'value of time' benefits offered by the high speeds. The low-boom requirement restricts all aspects of the design from wing shape and fuselage geometry, cabin and nacelle, through to aerodynamic performance, engine selection and propulsion integration to the applications of other novel technologies. Public acceptance plays an important role in the return of supersonic transport. A possible approach is the development of a flight demonstrator scaled to produce a representative reduced boom waveform signature and assess the response of the public.

Despite these challenges, considerable investment has been made in de-risking many of the enabling technologies and raising readiness levels. Many technologies are moving beyond theoretical and numerical analysis into the experimental and flight testing domains. The multidisciplinary design, analysis and optimization with higher-fidelity capacities can hopefully carry out in-depth studies founded on physics to limit the design space and thus to reduce future development costs.

The efforts from both the industry and the academy will speed up the process in bringing commercial supersonic aircraft back. The next-generation low-boom supersonic flight is expected in the next few years.

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